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New Brunswick Conservation
and Renewable Energy
Demonstration Program

Report for the

CANADA/NEW BRUNSWICK

CONSERVATION AND RENEWABLE ENERGY AGREEMENT

DB 44

SURFACE HEATED GREENHOUSE

N.B. POWER & N.B. COAL

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CREDA Project #2037

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The Conservation and Renewable Energy Demonstration Program Program is administered in New Brunswick by the Energy Secretariat and managed jointly with Energy, Mines and Resources Canada. The Program is designed to help demonstrate promising conservation and renewable energy technologies, to develop public awareness and understanding of these technologies, and to create employment in new or existing industries.

Through over 100 demonstration projects in New Brunswick, a wide variety of conservation and renewable energy technologies have proven to be technically sound and economically attractive. These demonstration projects should now provide a catalyst for commercialization and lead to widespread adoption of many of these proven technologies.

This final report is based on a project which was financially supported by the Energy Demonstration Program. For further information on other demonstration projects funded in New Brunswick under this program, contact:

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Le succès ainsi rencontré encourage la commercialisation des procédés les plus accessibles. Cela entraînerait certes l'adoption d'un grand nombre de ces techniques par les propriétaires de domiciles et par l'industrie privée.

Ce rapport final est basé sur un projet qui a reçu une aide financière du Programme de démonstration. Pour de plus amples renseignements, communiquez avec la:

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D E N I D E R E S P O N S A B I L I T E

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ABSTRACT

Greenhouse surface heating utilizes warm water from a thermal electric plant for greenhouse heating by cascading water over the outside of a greenhouse. Operated in this fashion the entire greenhouse acts as a heat exchanger. This eliminates the cost of auxiliary heat exchangers or heat pumps.

The purpose of this project was to demonstrate the degree to which surface heating can provide an economical supplemental greenhouse heating alternative.

Two ¼ acre glass greenhouses were constructed adjacent to NB Power's coal-fired power plant, at Grand Lake. Warm water from the plant was cascaded over one greenhouse and the second was heated conventionally, acting as a control to provide energy consumption comparisons.

Results show that energy savings increase directly proportional to water temperature and flow and inversely proportional to outside air temperature. Energy savings of 30% were achieved over one heating season. Potential energy savings of 40-70% are estimated at other Canadian Thermal Generating Plants, based on extrapolation of existing data. The technology also has application in other industries where there is a supply of warm water.

Economic savings are shown to be dependent on energy savings achieved and the cost of greenhouse heating fuel displaced by surface heating.

Payback for surface heating equipment at four selected Canadian plants ranged between 1½ to 9½ years.

KEY WORDS

Surface heating. Waste heat utilization. Economics of waste heat utilization. Greenhouse.

SOMMAIRE

La méthode consiste à chauffer une serre par la toiture en utilisant l'eau d'une centrale thermique qu'on fait couler en cascade sur la surface extérieure de la serre. De cette façon, la serre tout entière fonctionne comme un échangeur de chaleur. Ceci élimine le coût d'échangeurs de chaleur ou de thermopompes auxiliaires.

Le but de ce projet était de démontrer jusqu'à quel point cette méthode de chauffage peut servir de moyen de rechange économique pour le chauffage supplémentaire des serres.

Deux serres en verre d'une superficie de 1/4 d'acre furent construites à proximité de la centrale alimentée au charbon de Energie NB, au grand Lac. L'une des serres était chauffée par la toiture, tandis que l'autre, chauffée à l'aide d'un système de chauffage à l'eau chaude conventionnel, a servi de serre témoin dans le but de comparer la consommation énergétique.

Les résultats démontrent que les économies d'énergie sont directement proportionnelles à la chaleur et au débit de l'eau, et inversement proportionnelles à la température de l'air extérieur. On a réalisé des économies de 30 % en une saison de chauffage. A partir des données existantes, on peut estimer entre 40 et 70% les économies d'énergie potentielles aux abords des autres centrales thermiques au Canada. Cette technologie peut également s'appliquer à d'autres industries où on dispose d'une certaine quantité d'eau chaude.

Les avantages monétaires dépendent des économies d'énergie et du coût du combustible de la serre que remplace cette méthode de chauffage par la toiture.

Le recouvrement du matériel utilisé à quatre centrales canadiennes variait de 1 1/2 à 9 1/2 années.

MOTS CLES

Chauffage par la toiture. Utilisation de la chaleur résiduelle. Aspect économique de l'utilisation de la chaleur résiduelle. Serre.

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EXECUTIVE SUMMARY

The explosive rise in oil prices since 1973 has severely strained the Canadian vegetable greenhouse industry. During the period 1973-1984, Canadian oil prices have increased 500% but greenhouse vegetable prices have been unable to keep pace; with revenue from crops like tomatoes increasing only 175% during the same period. The impact of this has been serious losses of profitability for all, bankruptcy for some and an increased leakage in the Canadian economy resulting from increased purchase of southern USA produce. It has also jarred the industry into a search for cheaper greenhouse heating technologies.

Surface heating utilizes warm water from a thermal electric plant condenser for greenhouse heating by cascading the water over the outside of a greenhouse. Operated in this fashion the entire greenhouse acts as a heat exchanger, thus eliminating the need for auxiliary heat exchangers or heat pumps. Increased humidity problems are avoided because the water never comes into contact with the internal greenhouse environment. Freezing, a concern of many, is avoided by adjusting the flow of water so that the water temperature never drops below freezing.

The purpose of this project was to demonstrate that surface heating can provide an economical source of supplemental heat for a greenhouse. To facilitate acceptance by the industry, the project was intentionally built with all commercially available equipment and at near commercial size. It was carried out by NB Power and NB Coal at the Grand Lake Generating Station, 30 miles east of Fredericton, N.B.

Results confirm that there are three key factors which increase energy savings.

1. Energy savings increase as water temperature increases. This factor has the most pronounced impact on energy savings. Plants with minimum winter water temperatures of 65°F promise excellent savings.

2. Energy savings increase as outside air temperature decreases. Surface heating is suited to areas with long cold winters.

3. Energy savings increase as water flow increases. Based on the demonstration project a flow of 2000 gpm/acre is a good rule of thumb for practical operation.

Surface heating displaces fuel normally used to heat a greenhouse, consequently economic savings will be greatest in those regions like Eastern Canada where expensive oil would be displaced rather than in Western Canada where cheaper natural gas is used.

This investigation concludes that surface heating is financially attractive at sites where the combination of high energy savings and high greenhouse fuel cost prevail.

Examples of estimated energy savings and capital payback periods for surface heating equipment are outlined below for greenhouses at four selected Canadian thermal plants:

	Greenhouse Fuel Displaced	Estimated Energy Savings %	Payback Years
Sundance, Alberta	Nat. Gas	60	9
Pickering, Ont.	Nat. Gas	40	9½
Pt. Lepreau, N.B.	Oil	70	1½
Lingan, N.S.	Oil	50	2½

SOMMAIRE-RECOMMANDATION

La montée explosive des prix du pétrole depuis 1973 a sérieusement touché l'industrie canadienne des légumes de serre. De 1973 à 1984, les prix du pétrole ont augmenté de 500 % au Canada, tandis que les revenus des légumes de serre, dont le prix ne pouvait suivre ce rythme, n'augmentaient que de 175 % pendant la même période. Les répercussions de cette situation ont représenté d'importantes pertes de rentabilité pour tous les serristes, la faillite pour certains et une balance encore plus déficitaire pour le Canada en raison de l'achat d'un plus grand nombre de produits du sud des Etats-Unis.

Le chauffage par la toiture consiste à chauffer une serre en utilisant l'eau d'une centrale thermique qu'on fait couler en cascade sur la surface extérieure de la serre. De cette façon, la serre tout entière fonctionne comme un échangeur de chaleur, ce qui élimine le coût d'échangeurs de chaleur ou de thermopompes auxiliaires. Les problèmes d'humidité supplémentaire sont évités, car l'eau ne vient jamais en contact avec la partie intérieure de la serre. Quant au risque de gel, il suffit d'ajuster le débit de l'eau afin d'empêcher que la température de l'eau ne descende sous le degré de congélation.

Le but de ce projet était de démontrer que le chauffage par la toiture peut représenter une source économique de chauffage supplémentaire dans une serre. Pour mieux sensibiliser

l'industrie à ce projet, on n'a utilisé que du matériel qu'on peut trouver sur le marché et bâti une serre atteignant presque les dimensions des installations commerciales. Le projet a été réalisé conjointement par Energie NB et NB Coal à la centrale du grand Lac, à 30 milles à l'est de Fredericton (N.-B.)

Les résultats ont confirmé que trois facteurs principaux pouvaient jouer sur l'importance des économies d'énergie.

1. Les économies d'énergie sont fonction de la température de l'eau. Il s'agit du facteur le plus important en matière d'économie de l'énergie. Les centrales dont la température minimale de l'eau en hiver est de 65°F offrent d'excellentes possibilités économiques.

2. Les économies d'énergie sont fonction de la température de l'air. Le chauffage par la toiture convient tout particulièrement aux régions caractérisées par de longs hivers froids.

3. Les économies d'énergie sont fonction du débit de l'eau. Si on se fie au projet de démonstration, on peut considérer un débit de 2000 gpm/acre comme une bonne mesure de rendement pour une exploitation rentable.

Le chauffage par la toiture remplace le combustible normalement utilisé pour chauffer la serre. Les économies monétaires seront par conséquent plus importantes dans des régions comme l'est du Canada où cette méthode de chauffage remplacerait le mazout d'un coût élevé par comparaison avec le gaz naturel bien meilleur marché dans l'ouest du Canada.

Selon cette étude, le chauffage par la toiture offre des avantages financiers dans les régions où on constate à la fois des économies d'énergie importantes et un coût normalement élevé pour le chauffage de la serre.

Voici quelques exemples d'économies estimative l'énergie et de recouvrement du capital pour l'achat de matériel de chauffage de la toiture aménagé dans les serres de quatre centrales thermiques au Canada:

	Combustible remplacé dans la serre	Economies d'énergie estimatives %	Recouvrement nombre d'années
Sundance (Alberta)	Gaz naturel	60	9
Pickering (Ontario)	Gaz naturel	40	9 1/2
Point Lepreau (N.-B.)	Mazout	70	1 1/2
Lingan (N.-E.)	Mazout	50	2 1/2

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1 INTRODUCTION

In New Brunswick the price of residential furnace oil has risen a dramatic 500% during the period 1973 to 1984; from $0.27/gal in 1973 to $1.56/gal in 1984. During the same period the price of greenhouse vegetables in New Brunswick has lagged far behind this escalation, with wholesale tomato prices rising from $0.40/lb in 1973 to $1.10/lb in 1984; or a 175% increase. This fuel price explosion has seriously strained New Brunswick's greenhouse industry, resulting in significant production cutbacks, declining profitability for all, and bankruptcy in some cases.

During this same 1973 to 1984 period a waste heat utilization project undertaken at NB Power's Grand Lake Generating Station demonstrated that the cost of raising young salmon and trout can be reduced by 50% by raising them in warm water from a power plant (1). This successful demonstration of the economic benefits of waste heat utilization led to an assessment of its potential for heating greenhouses.

Two types of heat exchangers, wet or dry, have been used to extract greenhouse heat from warm water from a power plant. In the wet exchanger warm water flows through fibreglass pads and air blowing through the pads supplies heat to the greenhouse. Experience has shown that the high humidity levels resulting from this technique render it impractical (2). These humidity problems are overcome in the dry heat exchanger by passing the warm water through fin tube exchangers. Unfortunately the relatively low temperature of the warm water requires large banks of exchangers to supply greenhouse heat. This added capital cost has discouraged commercialization of the technology. Similarly, high capital costs and reluctance to accept high technology have discouraged the greenhouse industry from adopting heat pumps.

Research work in Illinois has shown that cascading warm water over the greenhouse surface can supply supplemental greenhouse heat without humidity problems or expensive heat exchangers. Humidity problems are avoided because the warm water never comes into contact with greenhouse air. By cascading water over the greenhouse, the entire greenhouse surface acts as a heat exchanger. This technique is known as surface heating.

Results from an experiment at Illinois Power's 1800 MW coal-fired Baldwin Plant during winter 1980 showed that surface heating reduced conventional greenhouse heat requirements by 1/3 (3). Furthermore, a computer simulation model predicted savings of 56% for a typical greenhouse heating season at the Baldwin site.

Based on the promise offered by this new surface heat technology, the greenhouse industry's urgent need for relief from high energy costs and the experience already gained from the aquaculture waste heat utilization work at Grand Lake, NB Power and NB Coal agreed to undertake a surface heated greenhouse demonstration at the Grand Lake Thermal Generating Station. The objectives of the project were:

1. To assess the energy and cost savings from a near commercial size surface heated greenhouse.

2. To assess the economic viability of surface heating technology.

3. To compare the quality and productivity of crops grown in a surface heated greenhouse with a conventional greenhouse.

4. To demonstrate available energy conservation measures.

5. To develop guidelines for transferring the technology to other Canadian sites.

2 PROJECT DESCRIPTION

2.1 SURFACE HEAT TECHNOLOGY

Despite freezing outdoor temperatures of 20°F a minimum greenhouse temperature of 59°F can be maintained, by cascading 86°F water at a rate of approximately 3000 gpm/acre over the greenhouse exterior (4). Greenhouse surface heating works because the entire greenhouse surface acts as a heat exchanger. It has been further reported that - "This system, of course, works best when the temperature of the water is above the temperature at which the greenhouse is to be maintained. Even if the water has a temperature at or even below that to be maintained in the greenhouse, considerable heating benefit can be derived from it. For example, suppose the outside temperature is 0°F and you wish to maintain the greenhouse at 65°F and the warm water available to you is only 60°F. Using a conventional heating system the outside surface of the greenhouse might be about 10°F. But by applying 60°F water the outside surface would be warmed to an average temperature of about 55°F, therefore considerably reducing the amount of heat leaving the greenhouse, and reducing the amount of conventional heat required to keep the greenhouse warm" (5).

The principal parameters which determine the effectiveness or energy savings achievable from this technology have been reprted by Dr. Paul Walker (4). These are discussed below:

2.1.1 Initial Water Temperature

The initial temperature of the water cascaded over the greenhouse has the most significant impact on the energy savings derived from surface heating.

Savings of 1/3 have been reported at the Baldwin Plant in Illinois during January, February and March, 1980. A computer simulation model predicted savings of 56%, using air and water temperatures which would be typical of a November to April heating season. This model further predicted annual energy savings would increase to 90.0% if monthly water temperatures were increased by 9°F. Many power plants produce warmer water than the Baldwin Plant. Predicted savings dropped to 28% when water temperature dropped 9°F.

The quantitative relationship between initial water temperature and heating benefit, shows that heating benefit increases linearly, as water temperature increases, Figure 1, (4).

2.1.2 Water Flow Rate

Heating benefit increases as the rate of flow over the greenhouse increases, Figure 1. At typical maximum expected temperatures of 86°F (or lower) there appears to be little practical value of increasing flow above the rate of 1500-3000 gpm/acre.

2.1.3 Outside Air Temperature

The heating benefit from surface heat increases linearly as outside air temperature decreases, Figure 2, (4). This relationship demonstrates that surface heating would provide greatest benefits in colder climates.

2.1.4 Length of Water Path

Figure 3, (4), shows that the length of water path has little effect on heating benefit provided that flow per unit area remains constant.

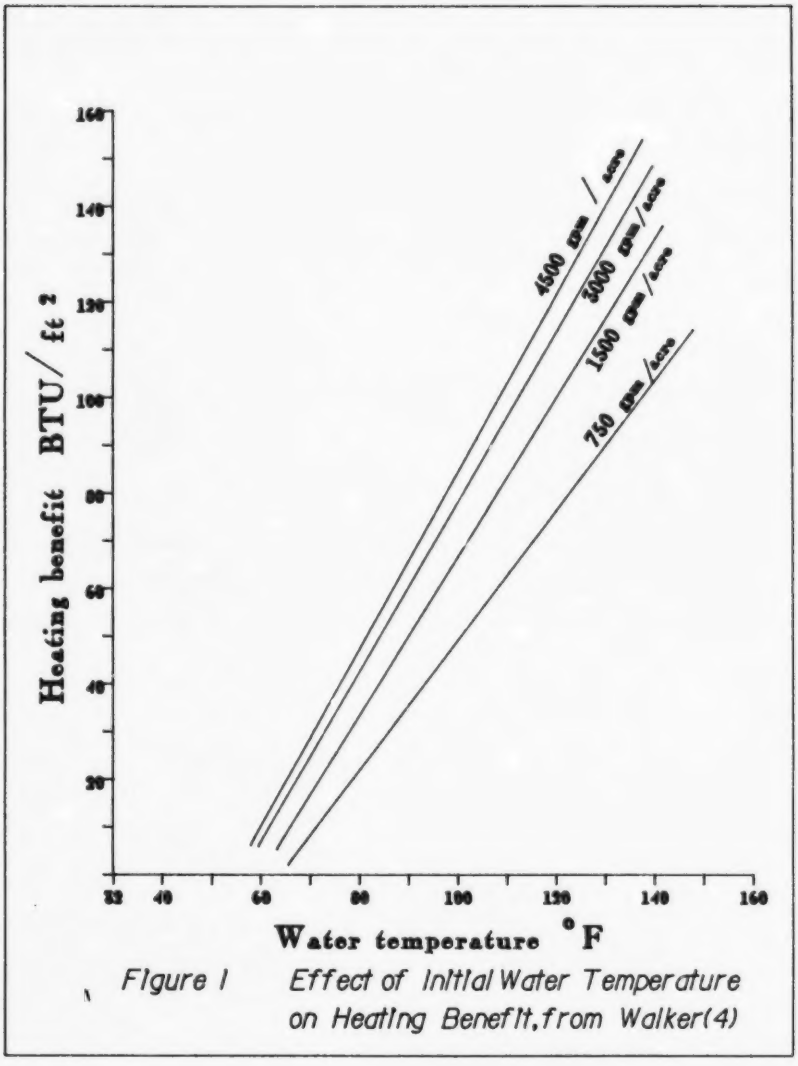


Figure 1 Effect of Initial Water Temperature on Heating Benefit, from Walker(4)

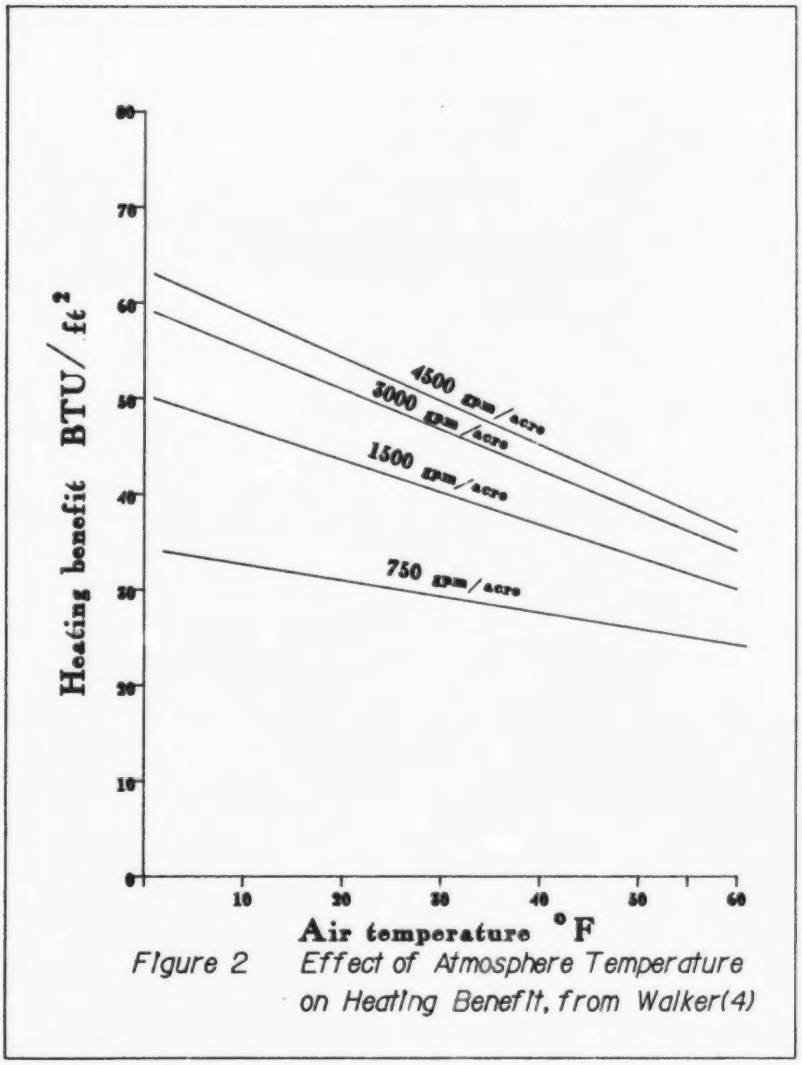


Figure 2 *Effect of Atmosphere Temperature on Heating Benefit, from Walker(4)*

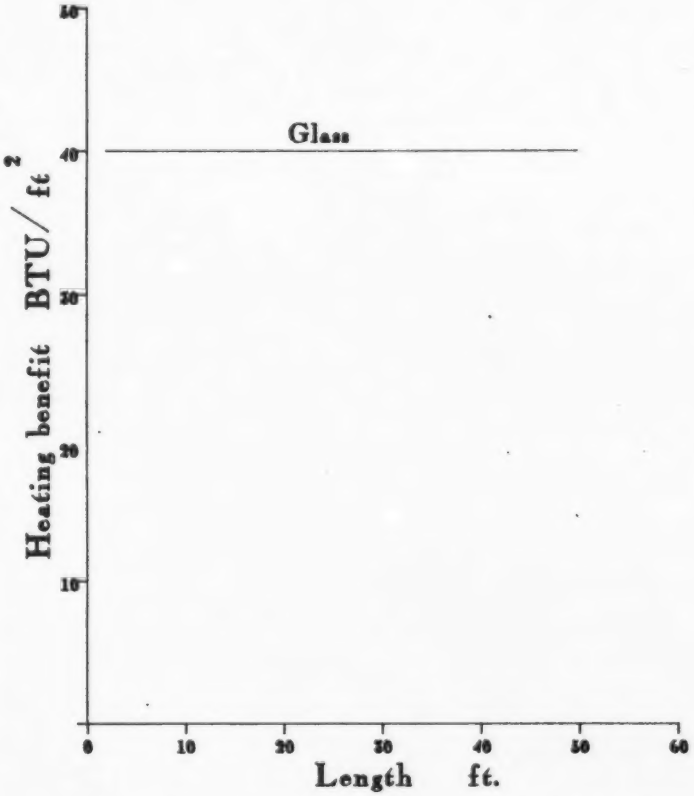


Figure 3 · Heating Benefit as a Function of Length of Water Path, from Walker(4)

2.2 DESIGN CONSIDERATIONS

The Grand Lake Thermal Generating Station is an 85 MW coal-fired plant, located 30 miles east of Fredericton, New Brunswick. The plant has 4 operating units which provides a reliable supply of warm water during the winter months. The plant's once-through cooling system supplies cooler water than would be expected from plants with recirculating cooling ponds or cooling towers. Table 1 shows that condenser water temperatures at the Grand Lake site are cooler than at the Baldwin Plant site.

TABLE 1

TYPICAL CONDENSER WATER TEMPERATURES FROM PLANTS AT GRAND LAKE, N.B., AND BALDWIN, ILLINOIS

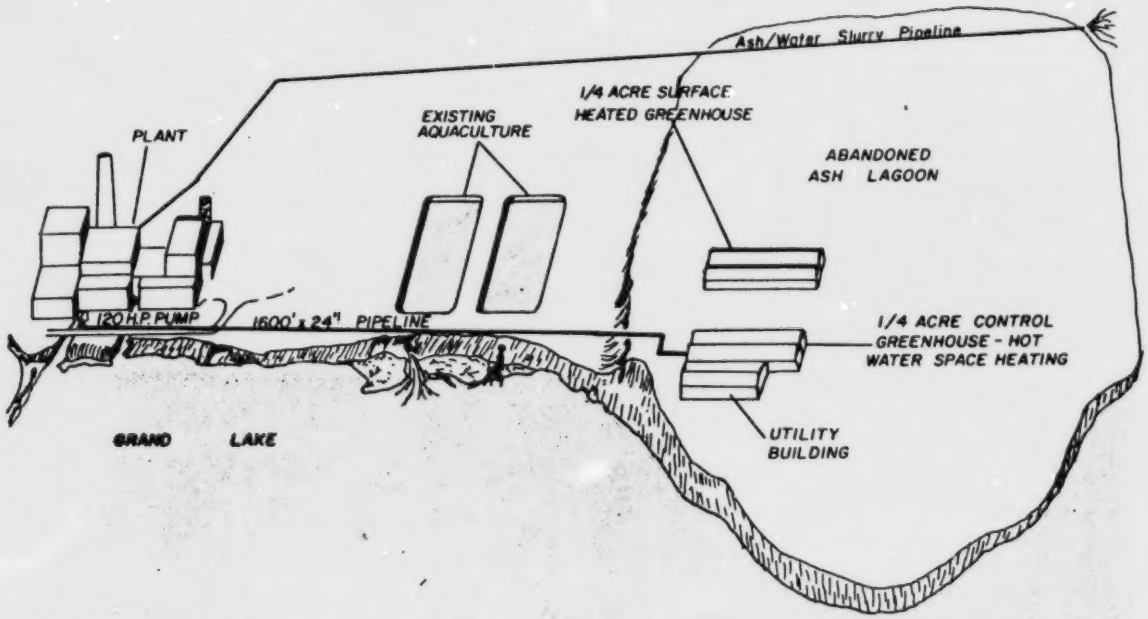
	Water Temperatures °F	
	Grand Lake	Baldwin
November	57	68
December	55	62
January	57	55
February	54	56
March	54	65
April	54	80

Construction of the greenhouse demonstration project at Grand Lake began in the fall of 1982. Monitoring of the heating benefits from surface heating continued from March, 1983 to March, 1984.

A site plan of the project is shown in Figure 4.

The greenhouse demonstration project is located on an abandoned ash lagoon 1500 ft from the plant. Two gutter connected

FIGURE 4 Site Plan of Greenhouse Demonstration Project Shows Surface Heated Greenhouse and Control Greenhouse Heated With Conventional Space Heating



glass greenhouse ranges 150' long x 67½' wide (approximately ¼ acre each) were constructed, Figure 5. The greenhouses were purchased as stock items, without any special features, from Paul Boers Greenhouse Ltd. Warm condenser discharge water at a rate of 1500 gpm/acre was cascaded over the roof of the experimental greenhouse. The control greenhouse was identical with the exception that it was heated conventionally. The energy consumption of each greenhouse was monitored during the entire heating season.

The project was intentionally built with commercially available equipment and at near commercial size to demonstrate to the greenhouse industry that no specialty equipment is required for surface heating.

A number of energy conservation measures were incorporated into the project. The long axis of the two greenhouses was oriented north-south to enhance light penetration. The north wall of each greenhouse, which received no sunlight, was fully insulated with plastic foam. During the heating season all side walls were insulated with an inflated double polyethylene sidewall cover. Water was not cascaded over the sidewalls.

Supplemental heat for the surface heated greenhouse and all space heating for the control was supplied by an industrial propane gas boiler. The heating system operated automatically to maintain the same temperature in each greenhouse.

Warm water pumped from the power plant via a pipeline was distributed along the ridges of the experimental greenhouse through 6" diameter aluminum pipes, Figures 6 & 7. Two rows

Figure 5 - Photo of Surface Heated Green House Site

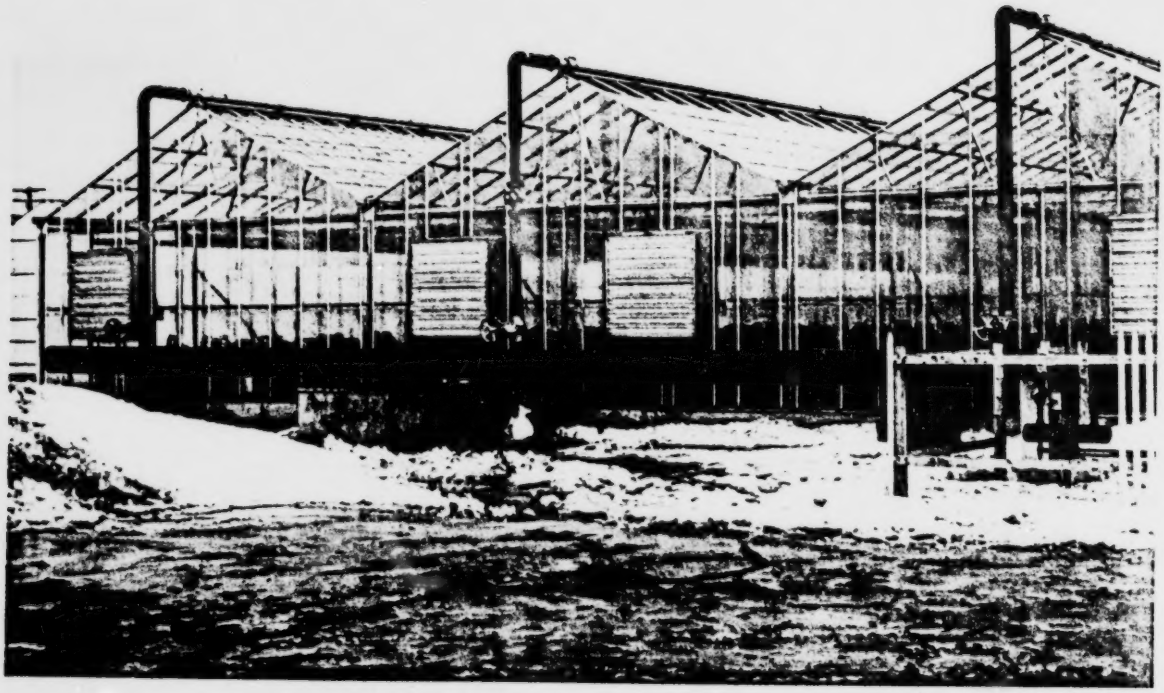


Figure 6 - Photo of Warm Water Distribution System

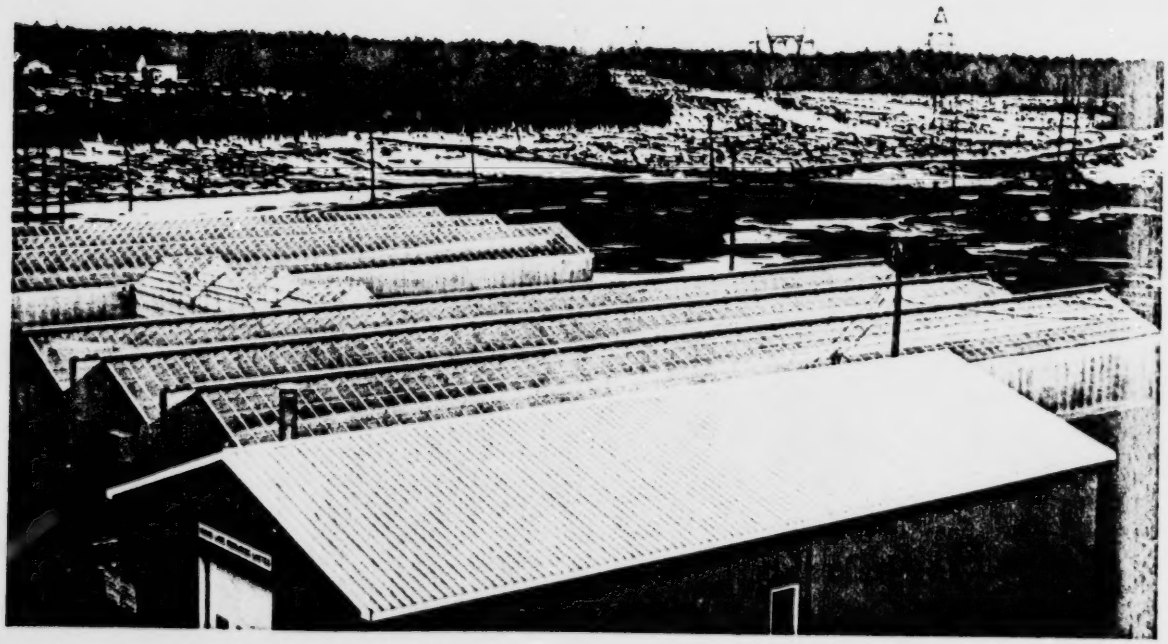


Figure 7 - Photo of Warm Water Distribution System

of 1/8" holes, spaced 3" apart (one row for each side of the greenhouse roof), were drilled in the pipe. This provided even water distribution over the roof. Run-off was collected in gutters and flow from the gutters was collected in pipes and discharged, Figure 8.

Tomatoes were the principal crop grown.

2.3 FOUNDATION PREPARATION IN AN ASH LAGOON

The size of the ash particles present in the lagoon are extremely fine, ranging from a maximum of 0.02 inches to a minimum of 0.0001 inches, with the predominant fraction being 0.002 inches. Because of its extremely fine size, ash is a very poor soil material for supporting a foundation. Without special treatment, foundations in ash will settle differently causing the above ground building to slump, bend or break. Clearly, this problem is particularly critical for a glass greenhouse. Furthermore, the problem was not anticipated during project planning and consequently no budget had been reserved for special foundation preparation.

Consultation with soil experts identified two solutions to the problem:

Alternative 1 - Wooden Piles

Driving wooden piles through the 25 foot deep ash layer and into original soil would provide a firm greenhouse foundation. This alternative would have cost $70,000 or an increase of 10% in project cost.

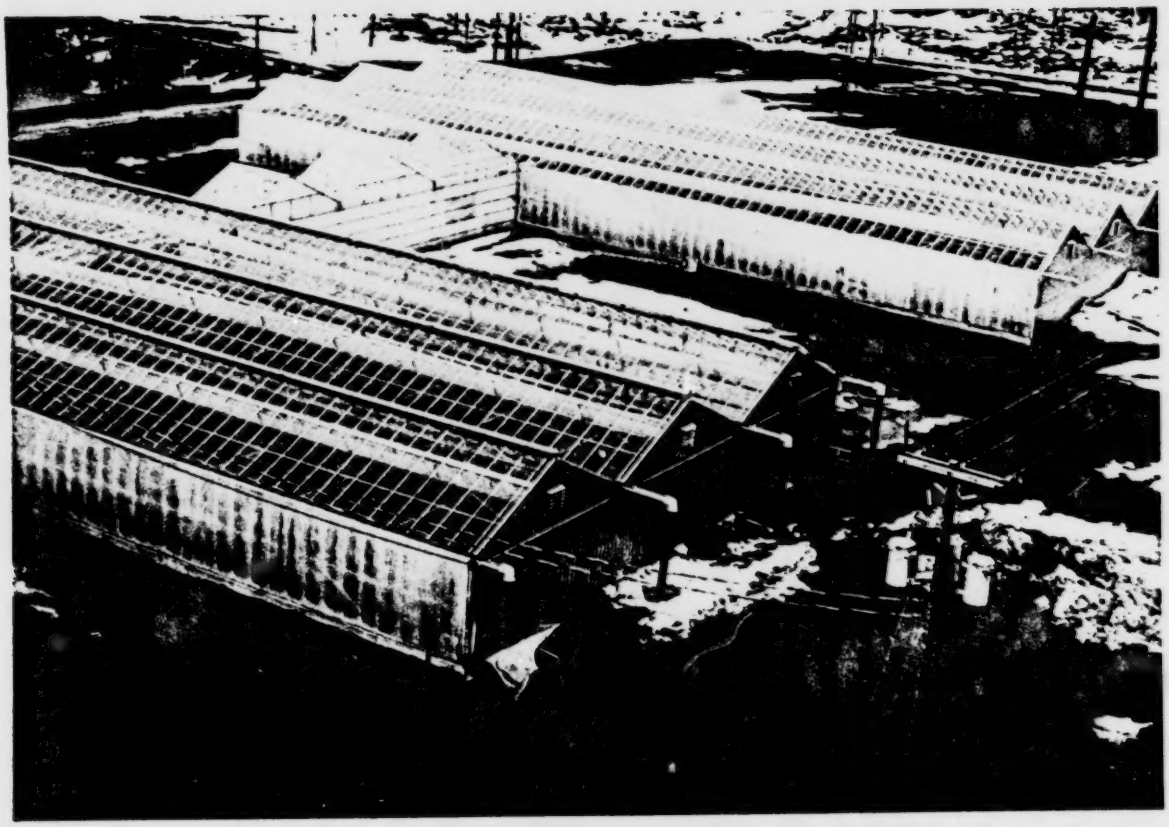


Figure 8 - Photo of Warm Water Discharge Piping and Extended Gutters

Alternative 2 - Dynamic Consolidation

In the dynamic consolidation process a 10 ton block of concrete is dropped from a crane and ash (or soil) is compacted through repeated blows. This alternative would have cost $35,000 or a 5% increase in project cost.

Neither of these alternatives were acceptable because both represented a significant increase in project cost (5-10%).

The final solution developed by the project team is shown in Figure 9, and described below:

Step 1 - consisted of augering a 2' diameter hole 8' down in the ash.

Step 2 - a one to two foot lift of crushed rock was placed in the augered hole.

Step 3 and 4 - repeated lifts of rock were hammered down through the bottom of the hole, until a densely compacted pressure bulb was created. The hammer was built from a 10 foot length of 16" steel pipe, with a solid steel dragline shaft welded inside. This 3 ton hammer was dropped 4 feet during the rock compaction process. Crushed rock was hammered through the bottom of the hole until refusal.

Step 5 - the remainder of the hole was then filled with compacted rock to within 3 feet from the surface. When completed, these stone columns would support 9000 pounds without any measurable deflection.

Step 6 and 7 - the remaining 3 feet of augered hole was filled with concrete. The footing on which the greenhouse support columns sit were embedded in this concrete.

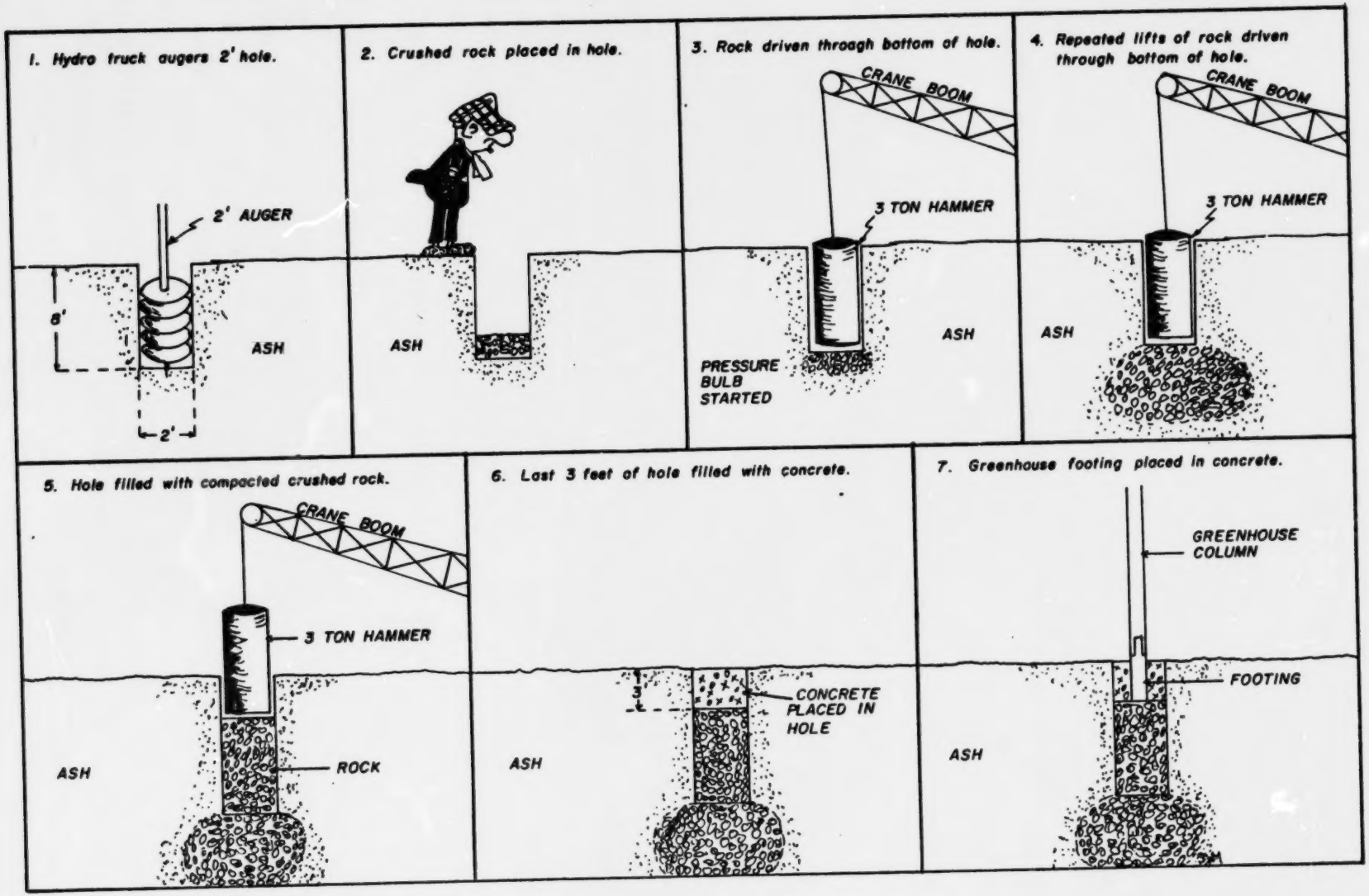


FIGURE 9 Construction Technique For Greenhouse Foundation

Preparation of the greenhouse foundations using this technique cost $5000; as compared to $70,000 for wooden piles or $35,000 for dynamic consolidation.

While it was not the intention of the project to do original research and development work on solving ash/foundation problems, the technique developed is inexpensive, effective and can be done by any general contractor. It also appears to have wide application for building any light industrial buildings on ash, or other poor base material.

2.4 MONITORING SYSTEM

The monitoring program for this project was developed to assess the performance and energy saving benefits of the surface heating concept. Both one quarter acre greenhouses were subjected to identical monitoring in order to compare the benefits and problems of conventional and surface heating methods.

The following operating parameters were monitored for one year from March, 1983 to March, 1984.

2.4.1 Temperature

Temperatures within the greenhouse were monitored with eight temperature probes in each greenhouse. This data was collected to ensure that both greenhouses were maintained at similar temperatures so that heat requirements could be accurately compared.

2.4.2 Relative Humidity

Relative humidity was measured in each greenhouse using a wet and dry bulb method, to determine the effect of constant flowing water on the humidity levels in the surface heated greenhouse.

2.4.3 Carbon Dioxide

Carbon dioxide levels were measured in both greenhouses by means of an infrared CO_2 analyzer to ensure that optimum levels were being maintained. A comparison of these measurements determined the effect of the watertight/airtight nature of the surface heated greenhouse on infiltration and CO_2 levels.

2.4.4 Solar Radiation

In order to determine the extent of any reduction of solar radiation through the water layer on the surface heated greenhouse, solar sensors were placed in each greenhouse. Total solar radiation was measured and compared outside and inside each greenhouse and photosynthetically active radiation was measured and compared between the two greenhouses.

2.4.5 Water Flow Characteristics

In order to determine an optimum range of water flows over the greenhouse roof, an ultrasonic flowmeter was used to calibrate valve rotations with water flow. Water temperatures were recorded in the header pipe and the gutter to determine the temperature loss down the roof.

2.4.6 Hot Water Heat

In order to determine the distribution of heat from the boiler to the two greenhouses, temperatures and water flow were measured in the greenhouse heating pipes. A calibrated BTU meter was used to convert this information to heat units.

2.4.7 Plant Production and Quality

Tomato production in each greenhouse was recorded. In this way the effects of surface heating on plant productivity have been determined.

A schematic of the layout of the monitoring is found in Figure (10).

The data on the above parameters was collected hourly in a Wynchester microcomputer and stored on magnetic disc.

2.5 ENERGY CONSERVATION BENEFITS

This project provided an opportunity to demonstrate state-of-the-art greenhouse energy conservation methods to commercial growers. The following energy saving methods were incorporated and evaluated.

2.5.1 Glass Lap Seals

The use of glass lap sealants on glass greenhouses eliminates air leakage through glass laps and significantly reduces infiltration losses of energy. In the case of the surface heating method, lap sealing is a coincidental benefit. Potential savings can range from 5 to 40%, depending on the age of the greenhouse. However, humidity levels could be higher and could cause condensation and dripping unless controlled by ventilation.

2.5.2 North Wall Insulation

Insulating an entire north wall has the advantage of substantially reducing heat losses while not significantly reducing overall light levels. The polyestyrene board with the aluminized inside layer serves to reflect available light into the greenhouse, at least partly eliminating dark areas. However, this may not be an acceptable conservation method for growers of light sensitive crops.

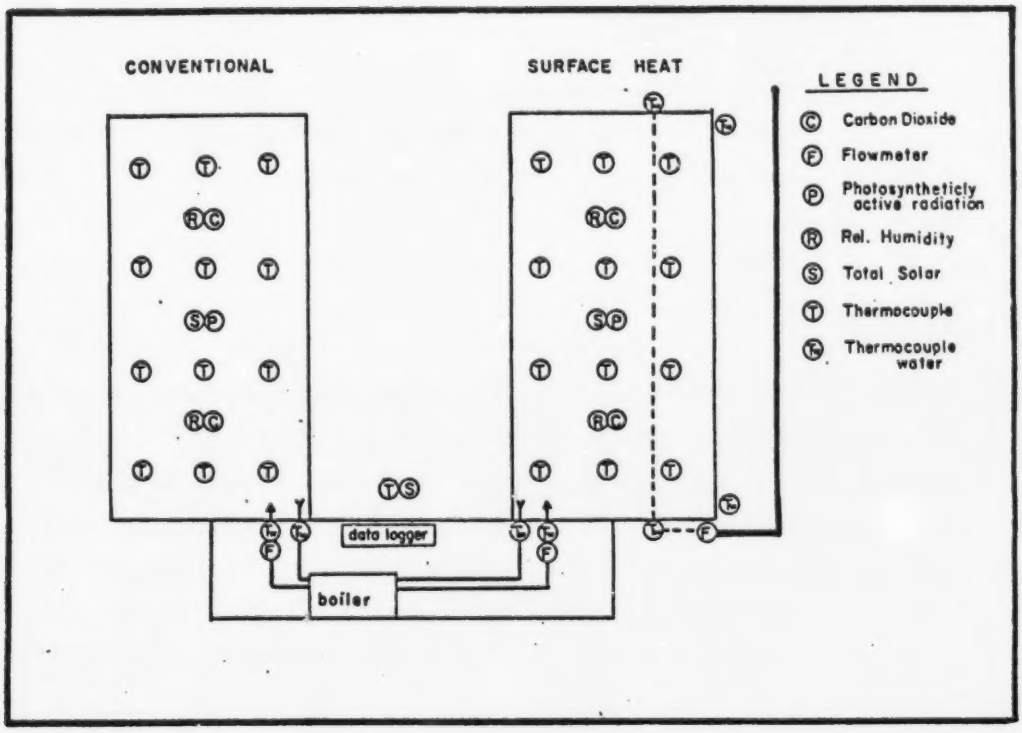


FIGURE 10 - LAYOUT OF GREENHOUSE MONITORING SYSTEM

2.5.3 Double Polyethylene Over Glass

Using double polyethylene on the sidewalls has a similar advantage to completely insulating the north wall, but without cutting out all of the sunlight. Studies conducted at Ohio State University and the Vinelands Research Station in Ontario reported energy savings of 57%, and although yields of some crops were less, the net effect is a saving of dollars to the grower.

2.5.4 Insulated Ventilation Fan Covers

Fan covers lose heat by conduction through exposed metal parts and by infiltration through the louvres. All fan covers in the greenhouses were sealed with a polyethylene sheet in the winter which was sufficient to eliminate infiltration and greatly reduce conduction.

2.5.5 Site Orientation

In order for a greenhouse to take advantage of as much solar energy as possible, it is obvious that the greenhouse should be oriented with the majority of the glazing facing in a southerly direction. At Grand Lake the greenhouse roof peaks were oriented North to South.

2.5.6 Furnace Efficiency

Significant energy savings can be achieved by maintaining boiler efficiency. Regular inspections and cleaning were carried out to meet this end.

2.5.7 Entrance to Greenhouse

Considerable heat loss is incurred with each opening of the greenhouse door. In order to minimize this, the facility was

designed such that the only access to the greenhouse was through the utility building.

2.5.8 Perimeter Insulation

The energy savings achieved from installation of below grade perimeter insulation are small, typically 3 to 6%. However, perimeter insulation is cost effective if installed during construction of a new greenhouse. This conservation feature was incorporated.

3 RESULTS

3.1 ENERGY SAVINGS

The energy used to heat the surface heated and control greenhouse are shown in Table 2 for the period April, 1983 to March, 1984. Energy consumption is graphically shown in Figure 11. Water flow during the period was held constant at a rate of 1500 gpm/acre. During this period the control greenhouse used 2486 million BTU and the surface heated greenhouse consumed 1735 million BTU. This demonstrates a 30.2% energy saving due to surface heating.

TABLE 2

MONTHLY ENERGY CONSUMPTION GRAND LAKE SURFACE HEATED GREENHOUSE AND CONTROL

Month	Control MMBTU/Month	Surface Heated MMBTU/Month	% Saving
September(1984)	50	36	28
October	298	253	15
November	383	291	24
December	451	298	34
January	497	288	42
February	314	222	29
March	310	216	30
April (1983)	101	79	22
May	82	52	37
TOTAL	2486	1735	Annual Saving 30.2%

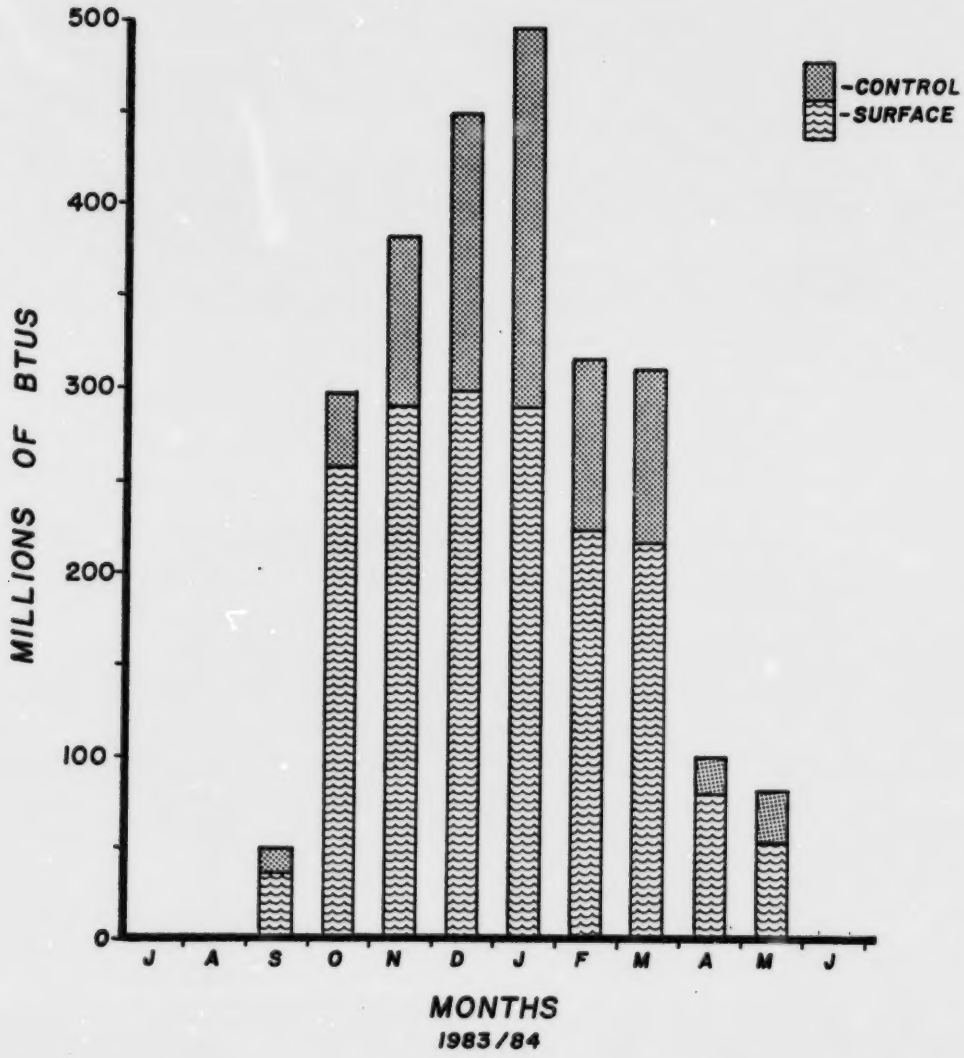


FIGURE 11 MONTHLY ENERGY CONSUMPTION

Surface Heated Greenhouse And Control

While the 30% saving reported at the Grand Lake site is lower than the 56% saving at the Baldwin plant in Illinois, the results are consistent with different site conditions; principally water temperature. Table 3 shows the air and water temperature at both sites. Recalling from Section 2.1 that initial water temperature has the greatest impact on energy savings, note that water temperatures at Baldwin are almost consistently higher than at Grand Lake and are significantly higher during fall and spring.

TABLE 3

TYPICAL AIR AND WATER TEMPERATURES AT GRAND LAKE AND BALDWIN

	Water Temperature, °F		Air Temperature, °F	
	Grand Lake	Baldwin	Grand Lake	Baldwin
November	57	68	30	41
December	55	62	20	32
January	57	55	15	28
February	54	56	17	32
March	54	65	28	41
April	54	80	40	54

Figure 12 shows a graph of typical Baldwin and Grand Lake monthly water temperatures which provided heating benefits of 56%, and 30%, respectively.

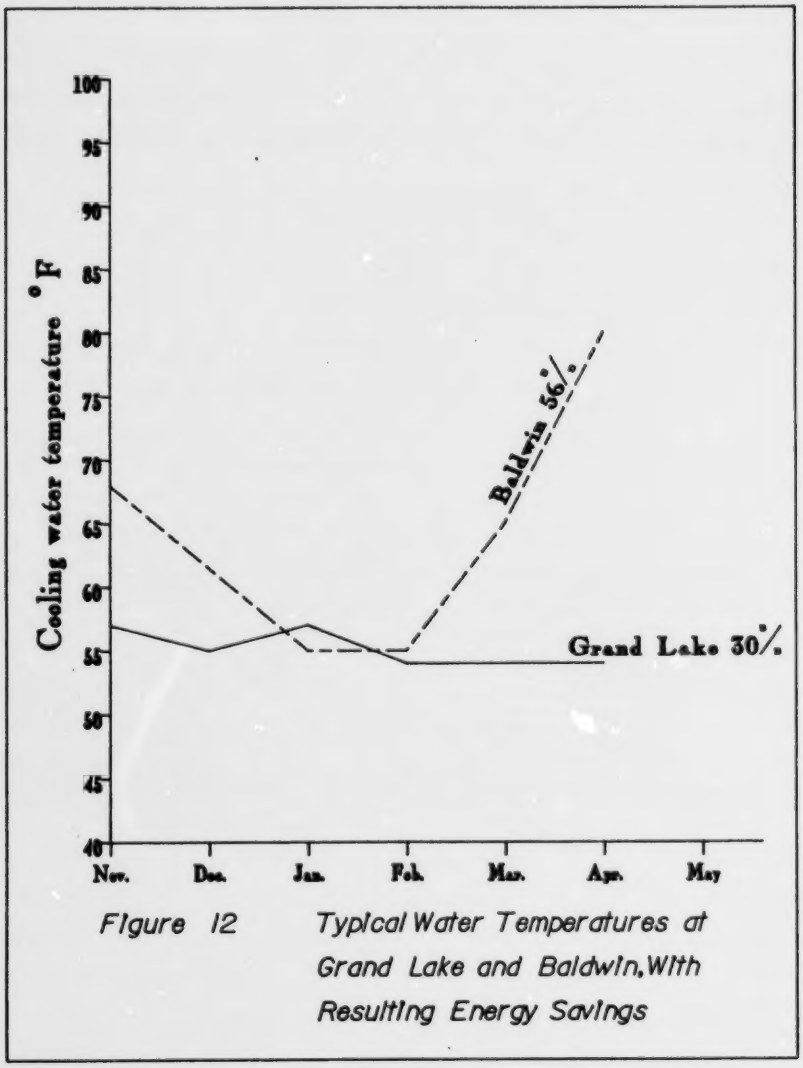


Figure 12 Typical Water Temperatures at Grand Lake and Baldwin, With Resulting Energy Savings

Based on the typical Baldwin water temperatures (56% saving curve) and the Grand Lake temperature regime, the following heating benefit relationships would be expected:

- during spring and fall savings would be lower at Grand Lake because of significantly cooler water temperatures

- during winter, savings at Grand Lake should be slightly higher because while water temperatures are about the same air temperatures at Grand Lake are lower. (Recall from Figure 2 that heating benefit from surface heating increases as outside air temperature decreases).

Based on these results, the following conclusions can be drawn:

1. The temperature of the water cascading over a greenhouse has a major impact on energy savings. Savings increase as water temperature increases.

2. Energy savings are greatest during the coldest winter months when energy consumption is highest. Savings at Grand Lake of up to 42% were achieved under these conditions.

3. Annual energy savings of 30% are achievable with the cooler water supplied from a once-through power plant cooling system, as demonstrated at Grand Lake.

3.2 GREENHOUSE ENVIRONMENTAL CONDITIONS

The environmental conditions in each greenhouse were monitored to determine the effect of surface heating on parameters such as relative humidity, carbon dioxide, total solar radiation and photo-synthetically active solar radiation. This is important since these parameters affect the productivity of the vegetable crop in each greenhouse.

The data was collected on an hourly basis from March 1983 to March 1984, with the equipment shut-down between mid-July and mid-September when no heating was required. The first step in analyzing the large quantity of data collected was to edit erroneous data which had been collected when equipment malfunctioned or data which was well outside a logical range. The remaining information contained over 6200 hours of data, or 78% of the total possible. A sample of the data output for a typical cold winter day is included in the appendix.

The initial presentation of the data is in the form of a simple descriptive statistical analysis shown in Table 4. This Table indicates the mean values for each parameter; the range of the values collected; and the standard deviations and coefficients of variance. The last two values are included to indicate the relative variability within the data but will not be referred to elsewhere in the report.

Frequency distributions were prepared for each parameter to determine the distribution of values in each greenhouse. The mode value and 90% distribution range are given in Table 5, i.e., the value most frequently recorded and the range which contained 90% of the values.

If each parameter observed in the two greenhouses had reacted exactly the same, one would have a theoretical relationship with a regression coefficient of 1. The theoretical and actual regression coefficients are shown in Figures 13-17.

These graphs indicate where the actual data acts according to the theoretical relationship i.e., where the two lines intersect, the actual regression has a coefficient of 1. As well these graphs indicate how far from the theoretical relationship the actual regression varies.

TABLE 4

DESCRIPTIVE COMPARISON OF ENVIRONMENTAL CONDITIONS IN THE SURFACE HEAT AND CONTROL GREENHOUSES

	Mean	Maximum	Standard deviation	Coefficient of Variance
Temperature (°C)				
Control	20.2	35.6	2.90	14.35
Surface - heated	19.9	36.5	2.93	14.72
Relative Humidity (%)				
Control	77.7	100	14.39	18.53
Surface - heated	81.4	100	11.57	14.22
Carbon Dioxide (ppm)				
Control	354	1771	333.59	93.99
Surface - heated	378	1907	370.85	97.91
Total Solar (watts/m^2)				
Control	37.6	836	82.95	220.75
Surface - heated	39.0	737	89.17	228.78
Photo-Solar*(einstiens)				
Control	1.15	53.8	3.04	264.32
Surface - heated	1.15	52.3	3.42	297.83

*photosynthetically active solar radiation

A Pearson correlation was computed for each parameter to determine the way in which a parameter in one greenhouse reacted with respect to the same parameter in the other greenhouse, for example, how the relative humidity values in the surface heated greenhouse reacted with respect to the relative humidity in the control greenhouse, Table 5. Correlation coefficients are a measure of intensity of association between two variables and range from -1 to +1. Correlations of -1 and +1 indicate a perfect negative or perfect positive correlation, respectively. Those correlations approaching 0 indicate less association between the two variables.

In order to determine the statistical similarity of the two data sets, i.e., the information about one parameter with respect to the same parameter in the other greenhouse, a simple T-test was computed. A T-test is a statistical analysis for testing the hypothesis that the means of two groups of data are equal. The results of these tests appear in Table 5.

In considering the relationships between the various environmental parameters between greenhouses, one must consider the conditions under which this experiment was carried out. The greenhouse was intentionally operated as a commercial facility and not as a research laboratory. While every effort was made to control most variables, it was not possible to control all variables which could effect the results, as could be achieved in a laboratory setting.

From a commercial greenhouse operators point of view, there are two key issues relating to surface heating. First, are the economic savings significant, and second, does cascading water over the greenhouse alter growing conditions in a way which could reduce crop yield and hence revenue.

In order to measure the benefits of surface heating, the auxiliary heating system was designed and operated to maintain

TABLE 5

RESULTS OF STATISTICAL ANALYSIS OF GREENHOUSE DATA

	Mode	90% Range	Correlation Coefficient	T-Test
Temperature (°C)			.82	not equal
Control	20	14-26		
Surface - heated	20	14-27		
Relative Humidity (%)			.43	not equal
Control	75	45-97		
Surface - heated	90	55-97		
Carbon Dioxide (ppm)			.96	not equal
Control	400	150-1200		
Surface - heated	400	150-1300		
Total Solar			.96	equal
Control	0*	0-200		
Surface - heated	0	0-200		
Photo-Solar			.28	equal
Control	0*	0-9		
Surface - heated	0	0-9		

*Zero readings represent the most frequent night time readings.

the same temperature in each greenhouse. By doing this, any reduction in supplementary heat in the surface heated greenhouse can be attributed to heating benefit from surface heating rather than simply a difference in temperature regime.

Similarly, the project was designed to determine how warm water cascading over the outside of the greenhouse affected growing conditions (e.g., humidity levels or light penetration) in the greenhouse. But, more importantly if there were environmental changes, how these would affect crop production and hence crop revenue.

The remainder of this section is intended to describe and interpret the differences between the environments which were maintained in the two greenhouses and the impact they had on energy savings and crop production.

3.2.1 Crop Production

As discussed in section 4.1.3, the difference in crop yield between the two greenhouses was insignificant. Thus, the variations in environmental conditions observed between the two greenhouses are not great enough to influence productivity and consequently would not impede commercialization of the technology.

3.2.2 Greenhouse Temperatures

In order to determine the effects of surface heating on energy consumption it was essential to maintain the same temperatures in each greenhouse. In this way any differences in energy consumption could be related back to the heating methods.

Temperatures within each greenhouse varied somewhat, i.e., each greenhouse would develop warm spots and cool spots. However, the air circulating system was very effective in ultimately rectifying this situation. Both greenhouses were

operated under the same daily plan of heating, ventilating, irrigating, etc., so as to allow for controlled comparison of energy input to each greenhouse.

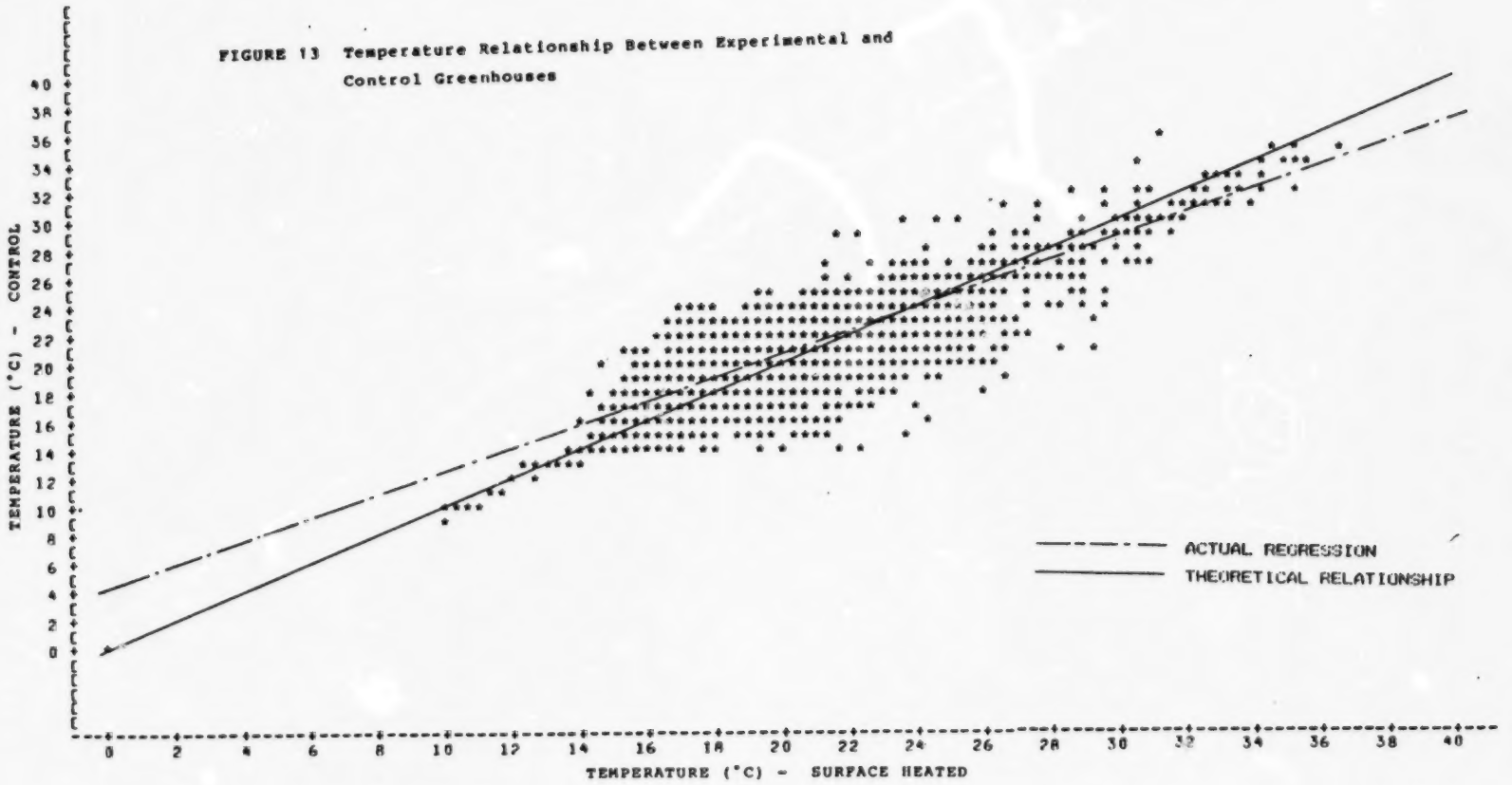
In comparing the temperatures in each greenhouse, as shown in Table 4, the mean temperatures differed by .3°C and the maximum temperatures differed by less than 1°C.

The frequency distribution of temperatures in the two greenhouses is almost identical with frequency peaks at 20°C, see Table 5. The plot of greenhouse temperatures, Figure 13, shows a good relationship between the actual and theoretical relationship, (i.e., the values in each greenhouse are almost the same). The correlation coefficient for the two sets of temperature data is .82. However, the results of the T-tests indicate that the two sets of data are not equal at the 95% level of significance. Thus, we cannot assume that the two data sets are significantly identical.

In spite of the fact that the T-test did not show the two data sets to be equal, there is strong evidence in the above mentioned analyses to indicate that the temperatures in the two greenhouses were essentially the same over the period of the experiment within the constraints of a normal greenhouse operating regime. In this regard we can conclude that the 30% energy saving between the two greenhouses cannot be related to temperature differences.

Visual observations made by operating staff during their daily schedule, and observations made of the computer printouts, indicated a moderating effect on temperature changes within the surface heated greenhouse. In the control greenhouse, inputs of heat may have been required on an hourly basis, whereas the surface heated unit required heat only every two to three hours.

FIGURE 13 Temperature Relationship Between Experimental and Control Greenhouses



3.2.3 Relative Humidity

Covering the outside of the greenhouse with water led to concerns about the effect that this would have on humidity levels inside the greenhouse. Elevated humidity levels can lead to increases in mold and fungus and to the spread of disease. To control this, humidity levels are reduced by ventilating with dryer outside air.

Relative humidity levels, compared in Table 4, indicated mean values about 5% higher in the surface heated greenhouse and a similar higher range of values. This elevated trend is confirmed in frequency distribution information in Table 5, and the regression information in Figure 14. The results of the T-tests indicate that the two sample populations are not equal. The correlation coefficient for this parameter is .43 (not a very strong correlation).

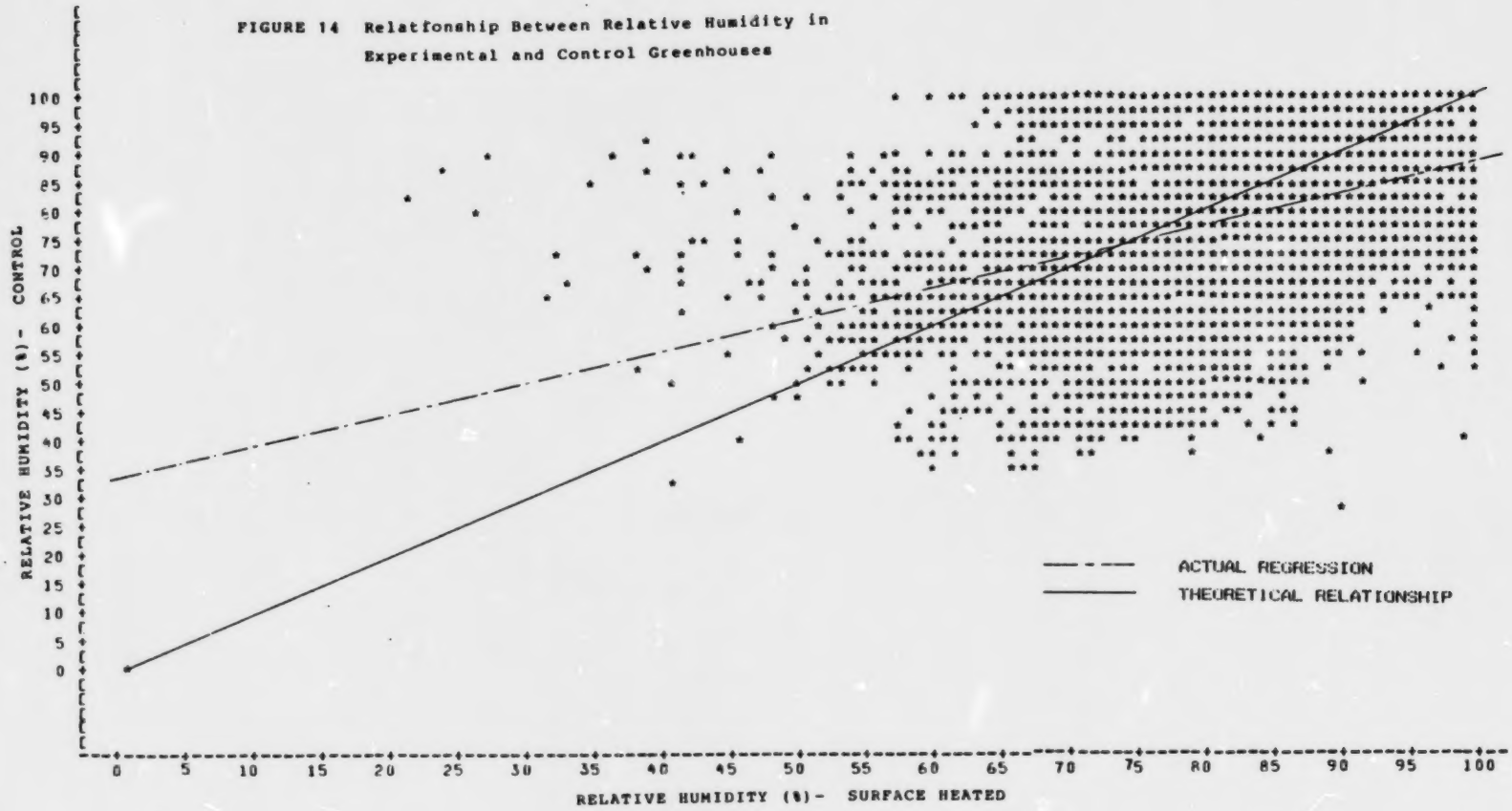
The slightly higher humidity levels in the surface heated greenhouse resulted from minor roof leaks at glass to metal joints. Also, water flowing over the roof formed an airtight seal (capillary action) where the glass panels overlapped. This reduced exchange of air through infiltration and consequently higher humidity levels were maintained.

Since there was no difference in the crop yield from each greenhouse, and no indication of increased disease in the slightly more humid greenhouse, we can conclude that the relative humidity levels in both greenhouses were within an acceptable range. The differences, therefore, are not significant.

3.2.4 Carbon Dioxide

Carbon dioxide is an important element in the photosynthetic process. This is the process by which plants use sunlight and

FIGURE 14 Relationship Between Relative Humidity in Experimental and Control Greenhouses



carbon dioxide to grow. Greenhouses require a certain amount of ventilation to replenish the carbon dioxide used in plant growth. Much of this ventilation comes from infiltration through the seams in the glass. Covering the whole greenhouse with water could drastically reduce the introduction of new carbon dioxide into the greenhouse, thus complicating plant growth.

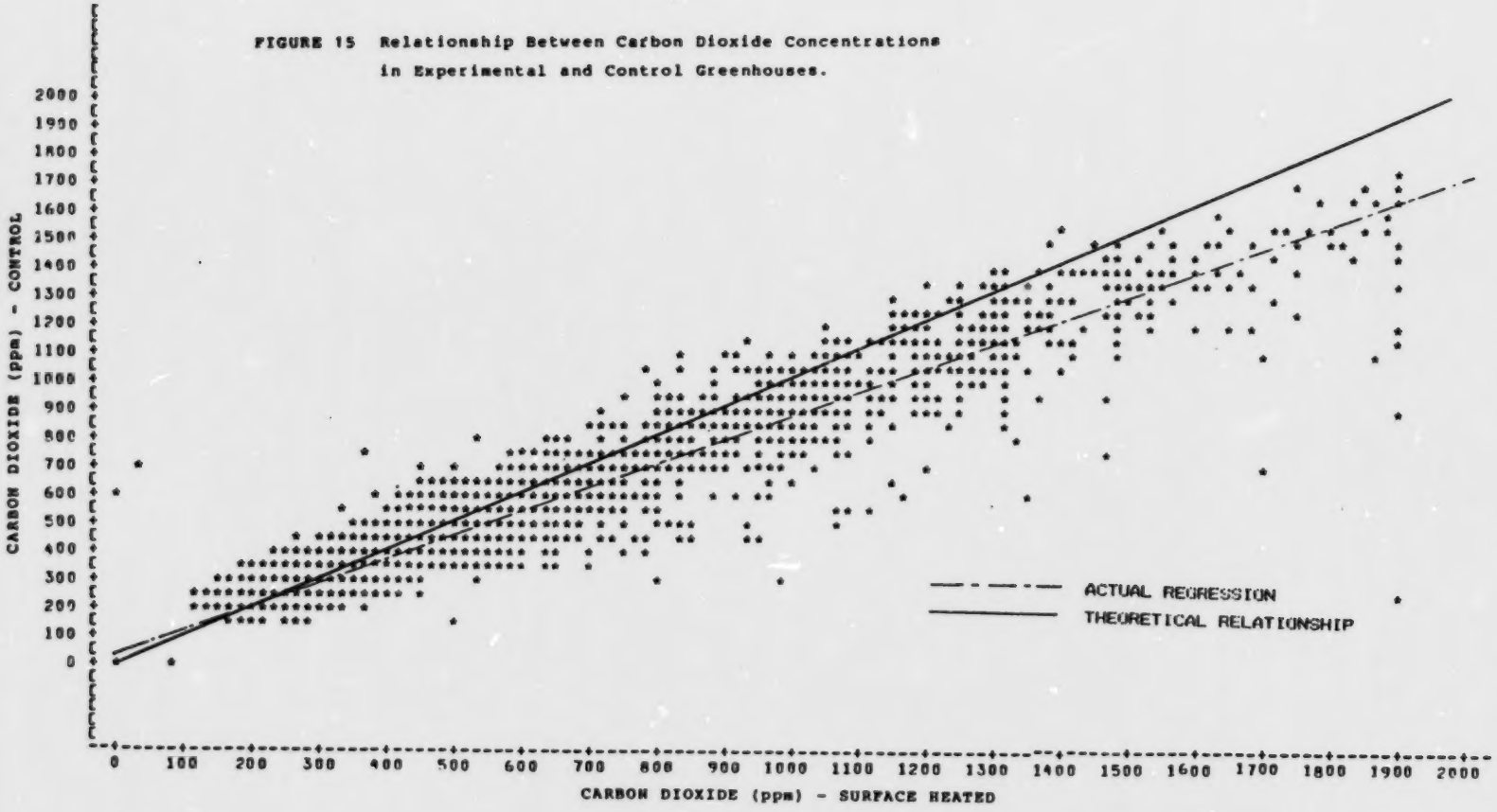
The mean carbon dioxide levels, in Table 4, indicate higher levels in the surface heated greenhouse, by less than 7%. The plotted data, Figure 15, indicates a close relationship between the levels in the two greenhouses. In the frequency distribution information, Table 5, maximum frequencies are at the same level, 400 ppm in each greenhouse and the values are within the same range. The correlation coefficient is .96, an extremely good relationship. However the T-tests indicate that the two sample populations are not equal.

The effects of ventilation and infiltration on carbon dioxide levels are similar to those on relative humidity (Section 3.2.4). As well, when looking at carbon dioxide levels in the greenhouse, one must consider that propane burners are used to increase CO^2 levels to improve crop quality and yield. CO^2 enrichment is an operational tool used equally in each greenhouse so that the impact of this increase in CO^2 should balance out over time when comparing the two greenhouses.

The excellent relationship expressed by the correlation coefficient is easily explained by the effect of sunlight on carbon dioxide consumption. At night the carbon dioxide consumption will be reduced equally in both greenhouses.

As with the analysis of relative humidity levels, the crop yield similarities make it difficult to conclude that the surface heat method had a significant impact on carbon dioxide levels. Though the levels may have varied, they have not gone outside the significant range for crop production.

FIGURE 15 Relationship Between Carbon Dioxide Concentrations in Experimental and Control Greenhouses.



3.2.5 Solar Radiation

Solar radiation is an obvious important influence on crop production. Initial concerns were expressed that water on the greenhouse roof could reduce light transmission due to reflection off the water, filtering due to the colour or turbidity of the water and possible filtering of the photosynthetically active portion of the light spectrum and this could lead to reduced crop yield.

The data for solar radiation are presented in Table 4. The mean values for total solar radiation and photosynthetically active solar radiation do not significantly vary between the two greenhouses. In Table 4, the mean values for total solar radiation differ by less than 4% and the photo-solar values are identical; the ranges differ by 12% and 3% respectively. For total solar radiation both the frequency distributions and Figure 16 indicate similar relations between the data. The correlation coefficient for total solar radiation in the two greenhouses is .96 and the T-test indicates that the two data populations are equal.

The total solar information, with the high correlation coefficient and the positive T-test, is a positive indication that the water on the roof has little effect on the intensity of solar radiation passing through the greenhouse glass.

For the photo-solar values, the frequency distributions are similar and the T-test indicates equal populations; however, in Figure 17 the actual and theoretical regressions are quite dissimilar and the correlation coefficient is only .28. This creates some question as to the similarity of the two data sets.

FIGURE 16 Relationship Between Total Solar Radiation in Greenhouses

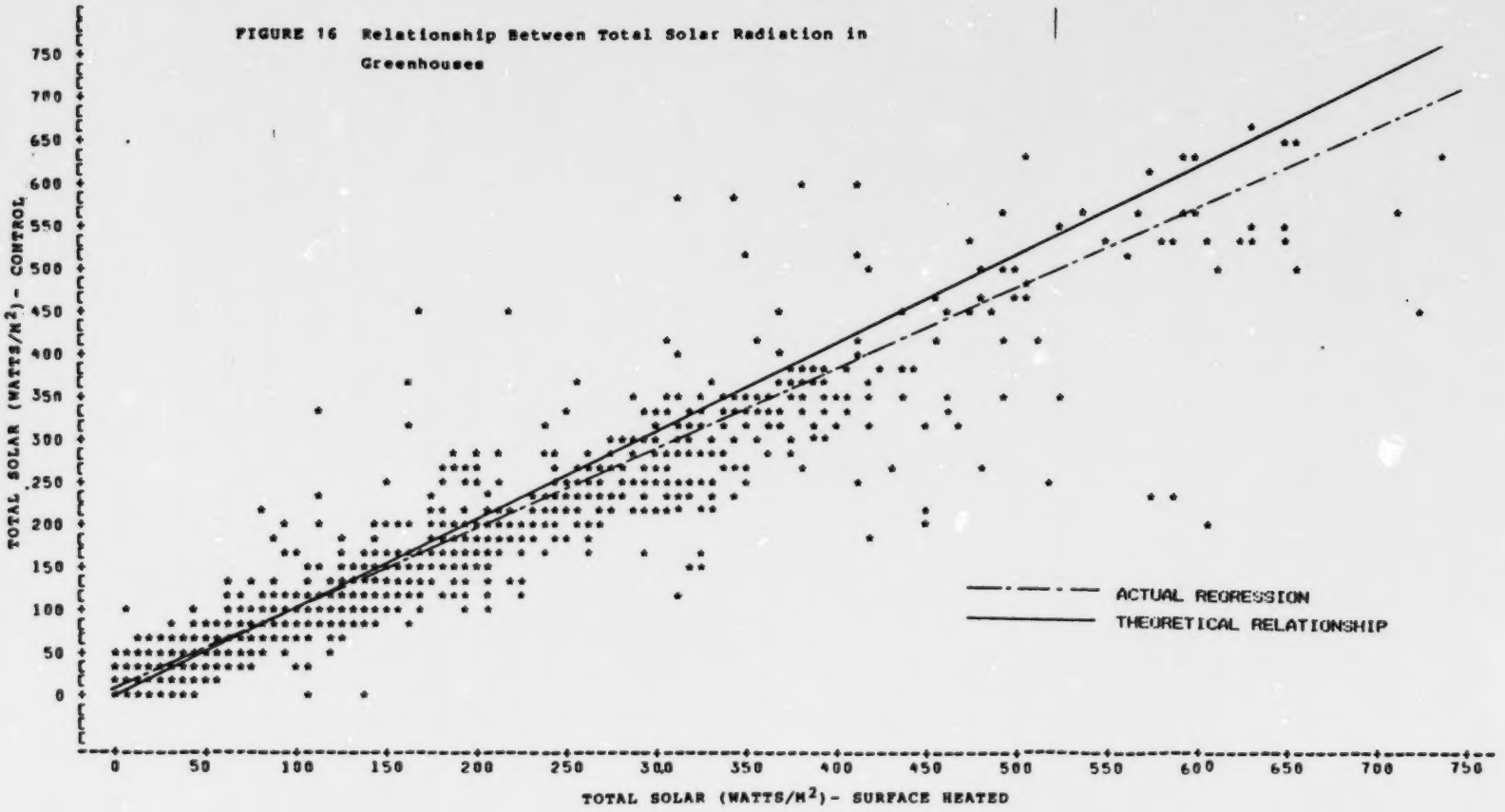
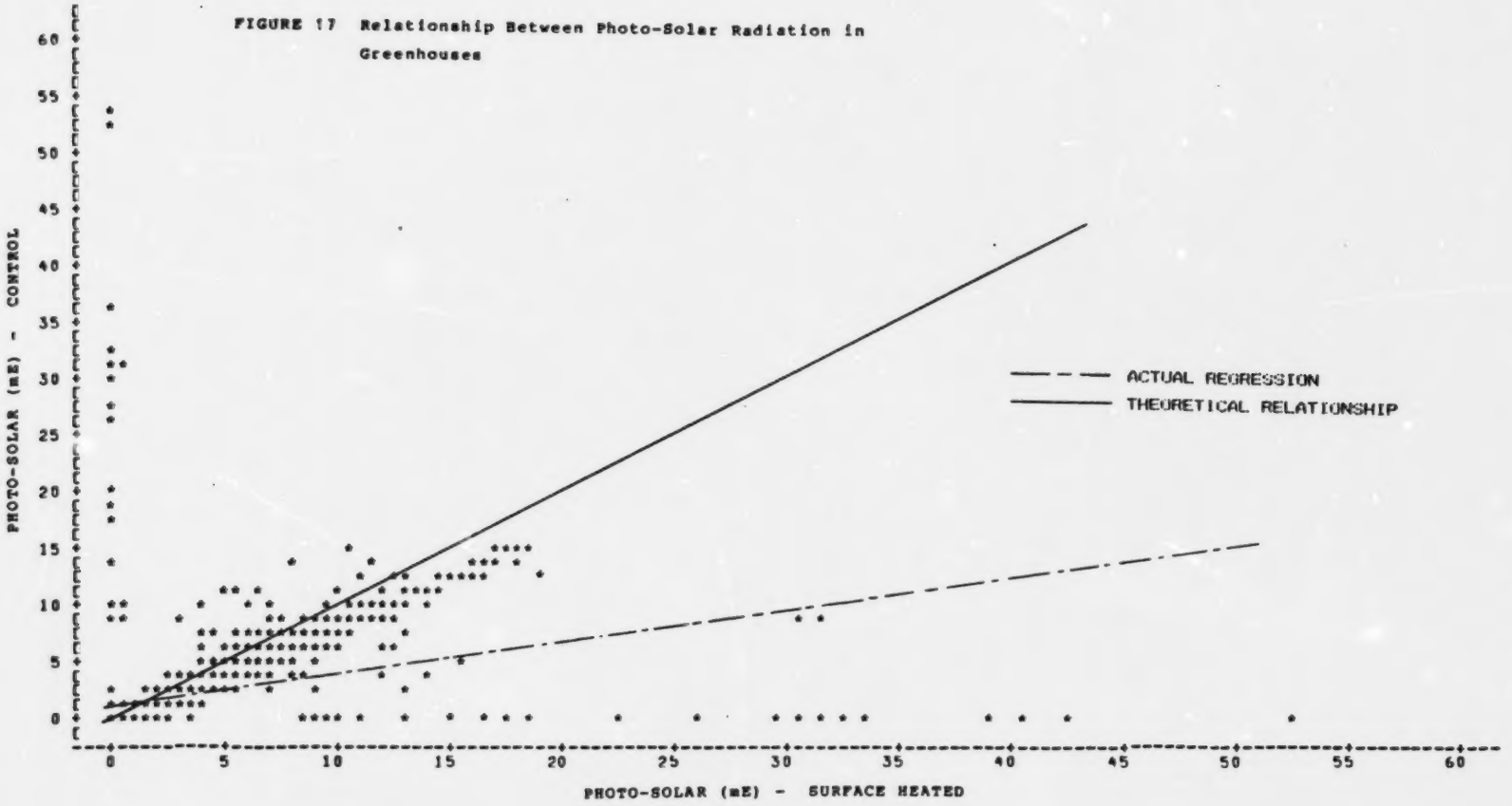


FIGURE 17 Relationship Between Photo-Solar Radiation in Greenhouses



The information on photosynthetically active solar radiation looks very similar with respect to the descriptive statistics, the frequency distribution and the results of the T-test. However the actual and theoretical relationships and the correlation coefficients indicate dissimilarities. When one considers the production of each greenhouse, it is reasonable to assume dissimilarities between other parameters in each greenhouse, while statistically significant, are not significant enough to effect production.

Other factors were also considered which could have contributed to variations in light levels between the two greenhouses. Dust generated in the area of the power plant and the ash disposal area would have a greater effect on reducing light levels in the control greenhouse than in the surface heated greenhouse since the flowing water served to keep the glass clean at all times. As well, early morning frost would appear on the control greenhouse but not on the surface heated greenhouse because of the warm flowing water. Frost occurred early in the morning when light levels were very low, and was quickly melted as light levels increase. The impact of this frost was probably minimal due to the low levels of light which would have been obstructed.

Hourly variations in solar radiation were observed between the two greenhouses; however, this could be due to a number of factors, primarily intermittent cloud cover. Solar readings were taken instantaneously on the hour, which at times resulted in different readings for each greenhouse due to partial cloud cover. This method was changed very early in the experiment to an average reading over a five minute period preceding each hour in an attempt to overcome this situation.

An unquantified observed benefit of the surface heated greenhouse is that the water layer diffuses the sunlight, thus eliminating shadows in the greenhouse.

4 ASSESSMENT OF GREENHOUSE SURFACE HEATING

The aim of the surface heated greenhouse project was to demonstrate this technology to the greenhouse industry, with the intention of encouraging commercialization if proven attractive. From the point of view of a greenhouse investor/operator, this technology would be attractive if it met two criteria:

1. Is the technology proven and simple to build and operate? (technological assessment)

2. Are meaningful cost savings achievable? (economic assessment)

These questions are discussed below.

4.1 TECHNOLOGICAL ASSESSMENT

4.1.1 Construction

The two greenhouses and associated equipment were intentionally purchased from commercial suppliers. Only the brackets used to attach the water delivery pipe to the ridge of the greenhouse required special fabrication. These simple devices were made in a local machine shop.

The greenhouse erection was supervised by a greenhouse building contractor, using local labour. Other construction was carried out by general contractors or project staff. Project staff supplied most of the design work required and construction management.

The capital construction was completed within budget.

Preparation of the greenhouse foundation on the ash lagoon, reported in Section 2.3, was the only specialty construction

technique developed and used. This was necessary because of the poor foundation conditions and not due to surface heating requirements.

The construction of the equipment required for surface heating was not a difficult phase of project construction. The cost of surface heating equipment is described later.

4.1.2 Operation

Operation of a greenhouse with surface heating was found to be simple, without any unmanageable problems. During the demonstration phase the surface heating system was operated by greenhouse personnel who had no specialty training in this area.

Initial problems were encountered when welds on the extended gutters, necessary for discharging water, were found to leak. This resulted in major ice build-up on the north end of the greenhouse, Figure 18. Sealing the welds with tar corrected this problem.

Freezing on the greenhouse roof, anticipated by many, was not found to be a problem because the rate of water flow over the greenhouse was sufficient that water temperature never dropped below freezing. This was the case for initial water temperatures of 50°F, flow rate of 1500 gpm/acre, and air temperatures of -35°F. Exit temperature under these conditions was 40°F. Minor freezing problems did occur when water outlet holes in the water pipe along the roof peak became plugged with algae creating dry spots on the greenhouse roof. In the area of reduced water flow at the edges of these dry spots freezing did occur at freezing temperatures. Bi-weekly flushing with higher pressure water prevented this plugging.

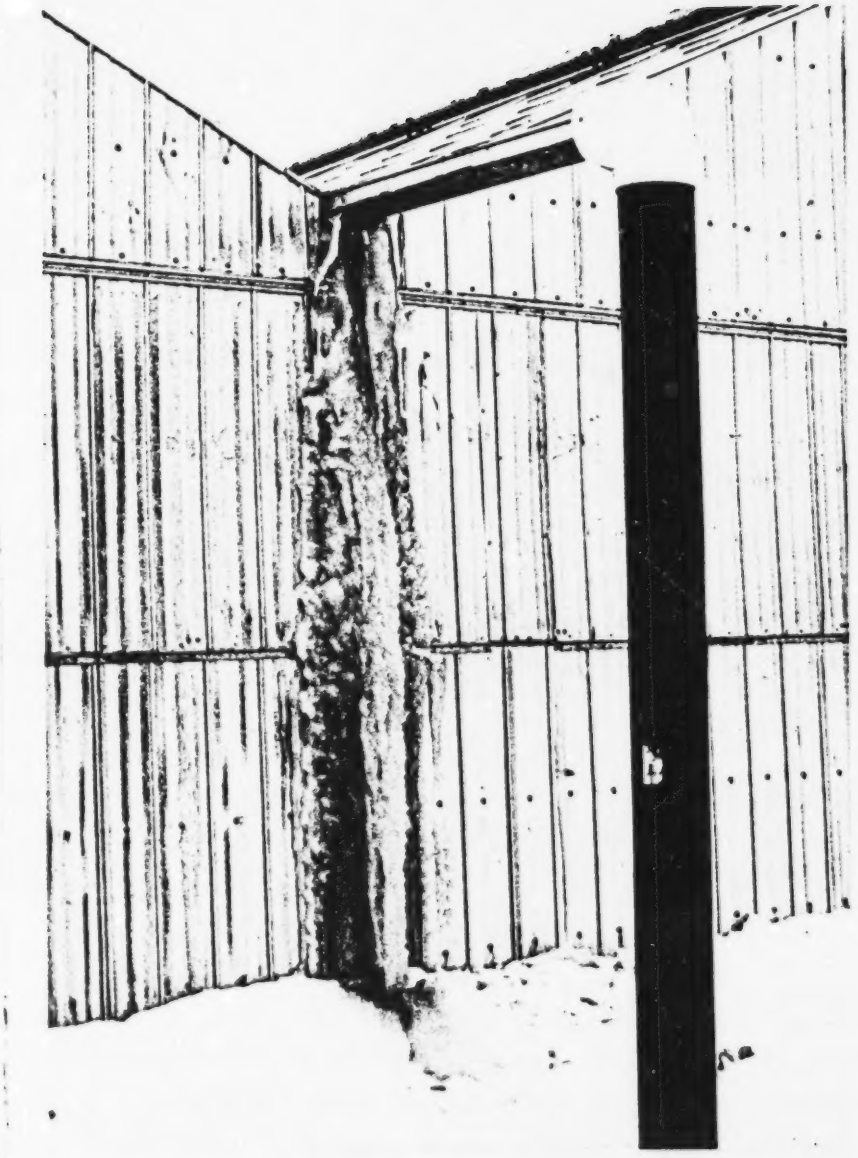


Figure 18 - Photo of Ice Buildup from Leaks at Gutter Welds

4.1.3 Crop Yield

Although environmental conditions varied somewhat in the surface heated greenhouse as compared to the conventionally heated greenhouse, this had little bearing on crop production. Table 6 shows the tomato yield from both greenhouses during the months when surface heating could influence crop production.

Table 6

TOMATO YIELD SURFACE HEATED GREENHOUSE VS CONTROL

	Surface Heated lbs	Control lbs
April, 1983	4446	4042
May	1082	1612
June	3681	4327
July	1857	1676
November	3902	3842
December	1583	1567
April, 1984	4501	4565
May	9048	9472
June	6559	5700
	36,659	36,803

As seen in Table 6 there is less than ½% difference in the crop yield from the two greenhouses. Based on this it can be concluded that the greenhouse environmental conditions created by surface heating have no significant influence on the production of tomatoes. In the opinion of New Brunswick Department of Agriculture officials tnere was no measurable difference in quality.

4.2 ECONOMIC ASSESSMENT

Once assured that the technology was readily manageable a demonstration that significant economic savings are achievable would be necessary.

Surface heating technology will provide the maximum economic benefit when the following conditions occur.

4.2.1 Conditions for Maximum Benefit

4.2.1.1 High Water Temperature - Figure 19 shows that energy savings at the Baldwin site would increase from 56% to 90% if water temperatures increases by 9°F above typical annual water temperatures. Similarly, savings drop to 28% if water temperature drops 9°F. This demonstrates the significant impact water temperature has on energy savings. The temperature regime/energy saving relationships shown in Figure 19 provide a guide which will be used to forecast savings achievable at other sites; discussed later in Section 4.2.2.

As a general rule electric power plants with once-through cooling systems supply cooler water than plants with cooling ponds or towers (recycling systems). Since the only Canadian plants with cooling ponds are located in the Prairie Provinces, it follows that the greatest energy savings would be expected there.

4.2.1.2 High Fuel Cost - Surface heating reduces the amount of fuel required to heat a greenhouse. Clearly, the economic benefit will be greater if expensive fuel is replaced, such as oil in Eastern Canada, rather than less expensive natural gas available in Western Canada. Consequently, the cost of available greenhouse heating fuels is a major factor determining the economic viability of surface heating, and the greatest benefits would be expected in Eastern Canada.

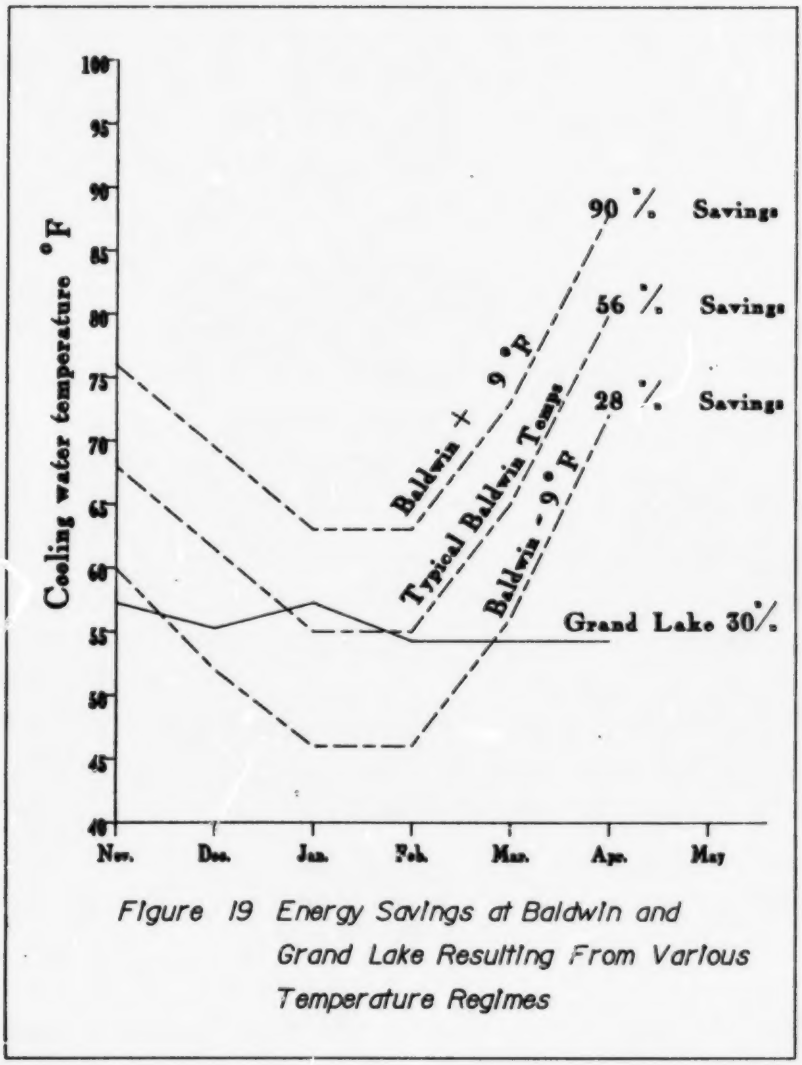


Figure 19 Energy Savings at Baldwin and Grand Lake Resulting From Various Temperature Regimes

4.3 ESTIMATED ENERGY SAVINGS AT SELECTED CANADIAN CENTRES

The preceding discussion has shown that energy savings from surface heating increase as the temperature of warm water available from a power plant increases and outside air temperatures decrease. With water temperature having a major impact on energy savings and air temperature a lesser impact. Later it will be shown that greenhouse fuel cost has more impact on economic savings (compared to energy savings) than either water or air temperature.

Figures 20 and 21 show the seasonal water temperature regimes experienced at both the Grand Lake and Baldwin sites, with measured energy savings of 30% and 56%, respectively.*

In addition, a simulation model developed during the Baldwin experiment predicted that an increase in water temperature of 9°F would provide an energy saving of 90%. Similarly, a decrease of 9°F would drop savings to 28%. These four curves provide a reference for estimating energy savings at other sites. The four reference curves in Figure 20 and 21 are labeled as follows:

Grand Lake	30%
Baldwin	28%
Baldwin	56%
Baldwin	90%

Also shown in Figures 20 and 21 are curves of the temperature of warm water released from power plants at:

Pickering, Ontario
Sundance, Alberta
Lingan, Nova Scotia
Pt. Lepreau, New Brunswick

Figures 20 and 21 are used to estimate the energy savings expected at these sites.

*Two Figures are used here because incorporating all information into one graph presented a confused Figure.

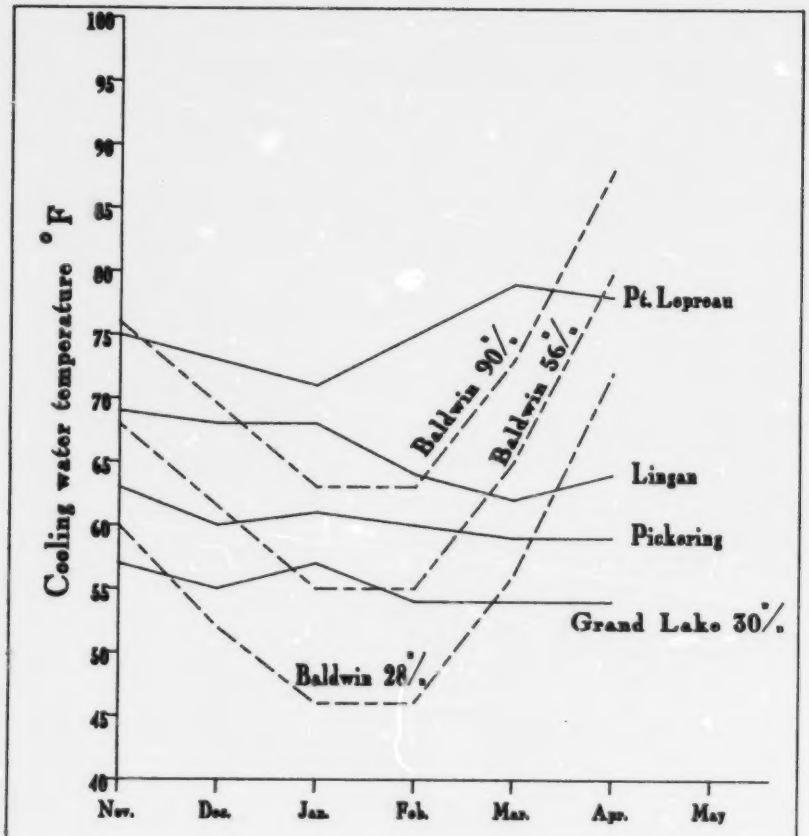


Figure 20 Typical Warm Water Temperatures From Baldwin, Grand Lake and Selected Canadian Plants

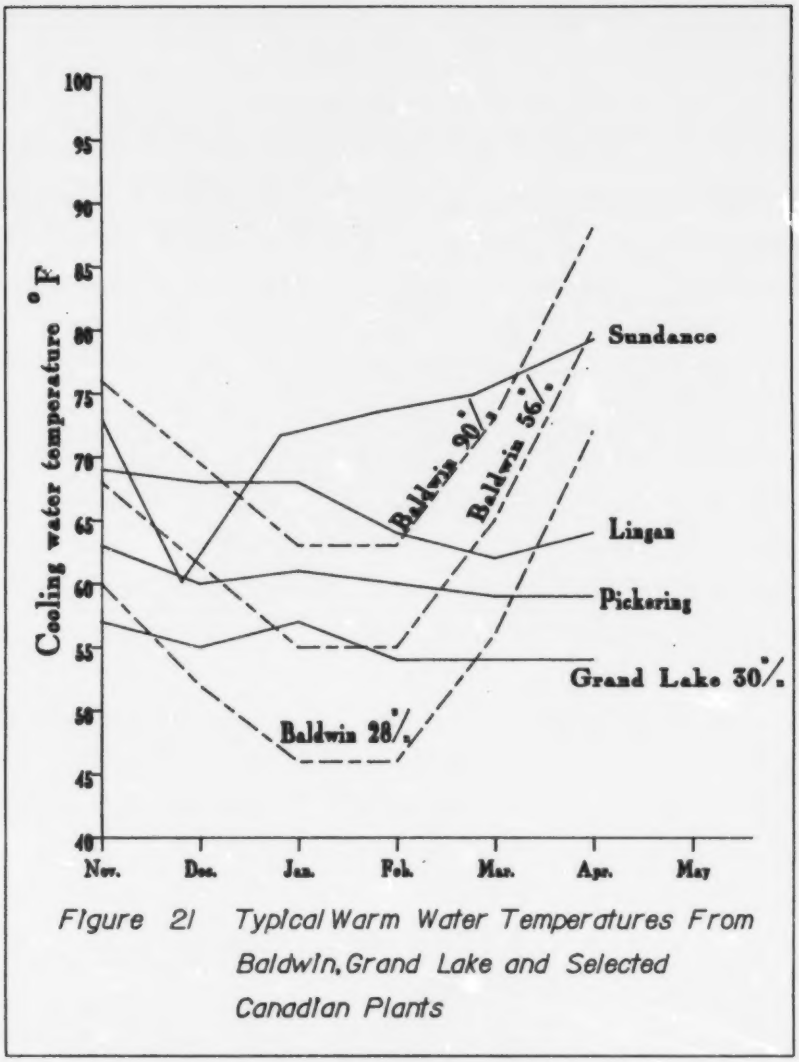


Figure 21 Typical Warm Water Temperatures From Baldwin, Grand Lake and Selected Canadian Plants

By inspection* it is seen that the temperatures at Pickering and Grand Lake behave similarly as the seasons progress; that is, temperature declines gradually in the fall, and remains steady at winter low until late spring. This is unlike the Baldwin temperature regime, where temperature declines rapidly in the fall, remains steady throughout winter, and rises rapidly in spring.

A 30% energy saving has been achieved with the water temperature regime experienced at Grand Lake, but temperatures at Pickering are consistently 4-7°F higher, consequently savings at Pickering should exceed 30%. During winter, when energy consumption is highest, Pickering temperatures are 4-5°F higher than those experienced with the Baldwin 56% saving regime. Therefore, savings during winter at Pickering should exceed those achieved from the Baldwin 56% regime. During fall and spring Pickering temperatures are below those on the Baldwin 56% saving regime, but higher than the Grand Lake 30% regime. In conclusion, the annual savings at Pickering can reasonably be expected to be between 30-56% and are estimated at 40%.

Similarly, by using this inspection technique, energy savings at the four selected sites are estimated to be as follows:

	Forecast Energy Savings %
Pickering	40
Lingan	50
Sundance	60
Pt. Lepreau	70

*While this technique of interpretation could be refined through computer simulation, the project contractor and sponsors agreed that the potential of surface heating can be assessed without this sophistication.

The cost of installing and operating a surface heating greenhouse would vary at the four selected sites and would depend on variables like pipeline length, pumping head and local building codes. Estimating these costs at all four sites is beyond the scope of this report, consequently a standardized capital cost of $110,000/acre for surface heating equipment is assumed, and an annual operating cost of $11,000 to pump water (1984$). These costs are based on the following assumptions that a standardized greenhouse would be built at all four sites, with the following specifications;

Greenhouse size	-	1 acre
Distance from plant	-	2000 ft (pipeline)
Pumping head	-	100 ft
Electric energy cost	-	4¢/kWh

To be attractive to business in the mid 1980's investments in energy conservation (or any discretionary investment) must promise to pay for themselves within 3-6 years. To meet this criteria, surface heating would have to provide net economic savings (value of energy savings less operating cost) within 3 to 6 years to pay back the capital cost of $110,000 for surface heating equipment.

Table 7 shows the annual cost of heating a traditional greenhouse, estimated energy savings from surface heating, and the payback period for the four selected sites.

The more stringent 3 year payback criterion is only met at Lingan, N.S., and Pt. Lepreau, N.B. Payback at both Pickering and Sundance exceeds 9 years and consequently it is likely to be unattractive to investors. It should be noted that energy savings at Sundance are greater than at Lingan. However, surface heating displaces relatively inexpensive natural gas at Sundance, whereas expensive oil is displaced at both Lingan and Pt. Lepreau. This demonstrates that high energy savings

TABLE 7

BENEFITS OF SURFACE HEATING AT SELECTED CANADIAN SITES

	Greenhouse Fuel Cost $/MMBTU	Annual Energy Consumption* MMBTU/Acre/Yr	Annual Heating Cost $/Acre/Yr	Forecast Energy Saving %	Value Energy Saving $/Acre/Yr	Net Saving** $/Acre/Yr	Payback Years	Return on Investment %
Sundance, Alberta	Nat. Gas @ $2.60	15,000	39,000	60	23,400	12,400	9	2.2
Pickering, Ontario	Nat. Gas @ $5.60	10,100	56,600	40	22,640	11,640	9½	1.0
Pt. Lepreau, N.B.	Oil @ $9.58	12,100	116,000	70	81,200	70,200	1½	63.3
Lingan, N.S.	Oil @ $9.80	11,300	110,700	50	55,350	44,350	2½	38.8
Grand Lake	Propane @ $11.00	12,500	137,500	30	41,250	30,250	3½	24.4

* Values from "Energy Conservation in Canadian Greenhouses: An Economic Analysis" (6)

** Net Saving = Value Energy Saving less $11,000/yr Pumping Cost.

and displacement of high cost greenhouse heating fuels are the key factors determining the profitability of surface heating technology.

The payback periods at plants like Pt. Lepreau and Lingan of 1½ and 2½ years and return on investment rates of 39 and 63% respectively, indicate that with the right combination of conditions surface heating technology is an attractive investment possibility for greenhouse heating.

Another measure of the value of surface heating is the comparison of total operating cost of a conventional oil heated greenhouse and one with surface heating. Oil heated greenhouses are common in Eastern Canada. The annual operating cost of a one acre oil heated vegetable greenhouse in Sydney, N.S., is approximately $300,000. The potential annual net saving which could be realized from a surface heated greenhouse located at nearby Lingan has been estimated at $45,400/acre/yr. A $45,000/yr reduction in annual operating cost represents a 15% saving in total operating cost. A major saving by any criteria!

In must be remembered, however, that each case must be assessed on its own economic merits and should include such factors as income taxes, land costs and so on, that are beyond the scope of this analysis. Also, the conclusions developed here relate to the benefits and costs of surface heating and not the economic viability of the vegetable greenhouse business.

In addition to the benefits outlined above, surface heating offers three unquantified benefits. First, surface heating reduces the demand for conventional make-up heat, consequently the capacity of a conventional greenhouse heating plant could be reduced. In the event of loss of warm water for surface heating, inexpensive propane heaters would supply emergency heat. Second, traditionally greenhouses are constructed with

multiple steeply sloped roofs to prevent snow build-up during winter. Since snow build-up is eliminated by surface heating the number and slope of roof sections could be reduced, thereby reducing the total roof area by as much as 10%. This would significantly reduce greenhouse capital cost and heating cost. Third, eliminating snow build-up eliminates the risk of greenhouse collapsing due to snow load.

In conclusion, this demonstration project has shown surface heating technology to be relatively easy to construct and operate. It has been shown to be financially attractive at sites where the combination of high energy savings and high greenhouse fuel costs prevail.

4.4 GUIDELINES FOR TECHNOLOGY TRANSFER

Surface heating should be an attractive greenhouse heating technology where the following conditions exist:

1) A reliable source of waste warm water is available, ideally with minimum winter temperatures above 65°F. In Canada sources of warm water would normally be found in the power generation, petrochemical, smelting, or refining industries.

2) High cost fuels, like oil, are used to supply greenhouse heat.

3) Winters are long and cold.

4) Space for greenhouse construction is available close to the source of warm water, with acceptable elevation differences to minimize pumping costs.

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A P P E N D I X

SAMPLE OF DATA OUTPUT FOR A TYPICAL COLD WINTER DAY

Sample of Data Output

January 13, 1984

	Air Temperatures (deg C)				Solar (W/M2aE)	Rel H (%)	CO2 (PPM)	Water (deg C)	HEAT (BTU x 10^4) (Cal x 10^6) This Hr.	Today
1: 0										
Control	20.4	19.7	19.6	18.7	6.5	83.0	504		7	7
	18.8	21.2	19.4	20.0	0.0		504		18	18
Surface	19.1	18.9	19.3	19.4	1.2	70.9	443	14.4	9	9
	19.0	19.8	19.6	19.9	0.0			4.8	23	23
Outside	-23.3				1.6			Saving (%)	-29	-29
2: 0										
Control	19.9	19.9	19.7	18.4	7.1	85.1	486		15	22
	18.9	20.9	19.6	20.2	0.0		488		38	56
Surface	20.0	21.0	20.4	21.2	1.8	64.6	414	13.6	5	14
	19.7	21.6	20.6	21.6	0.0			4.0	13	35
Outside	-22.3				0.2			Saving (%)	67	36
3: 0										
Control	19.8	19.3	19.4	18.8	6.0	85.8	496		10	32
	18.8	21.5	19.7	20.4	0.0		496		25	81
Surface	20.1	19.9	19.7	20.6	1.5	66.1	393	13.8	6	20
	19.9	19.9	20.1	20.7	0.0			3.8	15	51
Outside	-23.7				1.7			Saving (%)	40	38
4: 0										
Control	19.6	19.3	19.3	18.6	6.2	81.9	496		8	40
	18.8	21.3	19.2	19.6	0.0		496		20	101
Surface	18.9	18.9	18.6	19.3	1.7	72.9	421	13.8	3	23
	19.1	18.4	18.3	19.1	0.0			4.0	8	58
Outside	-24.7				1.1			Saving (%)	63	43
5: 0										
Control	18.9	18.6	18.9	17.9	6.0	88.2	481		13	53
	17.9	19.8	19.3	18.9	0.0		481		33	134
Surface	20.3	20.6	20.4	20.7	1.5	63.9	386	14.4	9	32
	19.6	21.1	20.4	20.7	0.0			4.2	23	81
Outside	-24.7				0.7			Saving (%)	31	40
6: 0										
Control	20.2	19.6	19.0	18.9	6.2	85.7	729		11	64
	18.9	21.1	19.8	20.1	0.0		729		28	162
Surface	20.9	20.9	20.3	20.9	0.5	65.4	665	14.4	4	36
	20.2	21.0	20.4	21.2	0.0			4.6	10	91
Outside	-25.7				0.4			Saving (%)	64	44
7: 0										
Control	19.6	19.3	19.0	18.4	7.1	84.5	1087		9	73
	18.3	20.7	19.1	19.3	0.0		1087		23	184
Surface	20.1	19.7	19.0	19.2	1.2	65.1	964	13.4	5	41
	19.4	19.9	18.4	19.7	0.0			2.8	13	104
Outside	-25.3				0.4			Saving (%)	44	44
8: 0										
Control	20.1	20.1	19.2	19.3	7.1	85.2	1280		9	82
	19.1	21.3	19.9	20.1	0.0		1280		25	207
Surface	18.8	19.0	18.8	18.9	1.0	70.4	1130	14.2	7	48
	18.1	19.0	18.4	18.9	0.0			4.0	18	121
Outside	-24.7				1.0			Saving (%)	22	4.

Sample of Data Output
January 13, 1984
(Cont'd)

	Air Temperatures (deg C)				Solar (W/M2-eE)	Rain (%)	CO2 (PPM)	Water (deg C)	HEAT ($BTU \times 10^4$) This hr.	HEAT ($Cal \times 10^6$) Today
9: 0										
Control	20.7	21.6	19.7	19.6	15.4	83.5	1395		13	95
	19.6	21.2	20.3	20.1	0.0		1395		30	240
Surface	18.3	16.6	18.6	19.0	1.4	69.8	1369	12.6	3	51
	18.8	18.9	18.4	18.8	0.0			2.8	8	129
Outside	-24.7				7.3		Saving (%)		77	46
10: 0										
Control	20.3	20.6	19.8	20.2	33.4	86.0	1170		6	101
	20.1	20.2	20.9	20.6	0.1		1170		15	255
Surface	18.6	19.0	18.7	18.6	15.0	69.7	1206	14.4	1	32
	19.0	17.7	18.1	18.4	0.2			2.4	3	121
Outside	-22.3				59.0		Saving (%)		83	49
11: 0										
Control	19.0	18.9	18.6	19.6	71.0	36.7	997		9	110
	19.4	26.0	19.7	20.0	0.5		997		23	278
Surface	19.3	18.9	19.4	20.1	41.4	79.1	1053	15.2	4	56
	20.0	18.4	18.8	19.4	1.0			3.2	10	141
Outside	-18.7				118.4		Saving (%)		56	49
12: 0										
Control	20.7	19.3	19.7	20.2	123.0	87.4	848		0	110
	20.1	16.4	20.7	20.7	1.4		848		0	278
Surface	21.6	20.6	20.6	20.8	88.8	75.6	931	12.6	0	56
	21.2	18.3	19.9	20.8	2.2			4.6	0	141
Outside	-15.3				266.9		Saving (%)		100	49
13: 0										
Control	21.4	18.6	19.3	20.7	148.7	91.0	758		4	114
	20.8	15.7	21.0	21.0	2.9		758		10	288
Surface	22.6	22.9	22.3	22.1	170.9	75.6	827	12.6	0	56
	23.0	19.5	21.2	22.8	3.0			4.6	0	141
Outside	-15.0				391.6		Saving (%)		100	51
14: 0										
Control	22.7	19.7	20.6	21.8	95.7	89.0	683		0	114
	22.2	18.3	21.8	21.8	1.4		683		0	288
Surface	22.1	21.2	20.8	21.3	88.0	78.7	749	12.6	0	56
	23.2	18.8	19.8	20.9	1.9			4.8	0	141
Outside	-13.3				297.5		Saving (%)		100	51
15: 0										
Control	21.3	19.0	19.2	20.0	76.9	89.0	561		7	121
	20.1	18.1	20.2	20.4	0.9		561		18	306
Surface	21.2	19.3	19.6	20.1	60.4	75.6	674	12.9	2	58
	20.8	18.2	18.2	19.2	1.4			4.4	5	146
Outside	-13.7				173.9		Saving (%)		71	52
16: 0										
Control	19.3	18.9	18.9	18.6	36.4	90.9	528		7	128
	18.7	18.5	19.3	19.4	0.2		528		16	323
Surface	20.3	20.0	19.2	19.8	15.0	77.9	603	12.6	3	61
	20.4	18.3	19.1	19.6	0.4			5.4	8	154
Outside	-12.7				52.4		Saving (%)		57	53

Sample of Data Output
January 13, 1984
(Cont'd)

	Air Temperatures (deg C)				Solar (w/M2;uE)	RelH (%)	CO2 (PPM)	water (deg C)	HEAT ($BTU \times 10^4$) ($Cal \times 10^6$) this hr.	Today
17: 0										
Control	20.6	20.2	19.7	19.4	16.3	89.0	552		8	136
	19.4	20.6	20.6	20.8	0.1		552		20	340
Surface	19.9	19.3	19.2	19.0	6.5	75.7	544	13.(	7	68
	19.7	18.3	18.6	19.6	0.1			5.2	18	172
Outside	-13.7				16.1			Saving (2)	.3	5
18: 0										
Control	22.2	21.6	21.3	20.e	3.9	76.1	520		8	144
	20.8	22.5	21.7	21.7	0.0		520		29	3e4
Surface	18.7	19.0	18.1	18.8	0.5	72.3	512	12.e	2	70
	19.3	18.3	16.2	18.9	0.0			5.0	5	177
Outside	-13.3				0.5			Saving (2)	75	51
19: 0										
Control	20.8	20.4	19.9	20.0	3.9	85.1	504		8	152
	20.6	21.0	20.7	20.7	0.0		504		15	379
Surface	20.1	20.4	19.9	19.9	0.2	65.8	496	11.4	7	77
	19.4	20.9	20.1	20.7	0.0			5.6	16	194
Outside	-14.0				23.1			Saving (2)	-17	49
20: 0										
Control	20.6	20.3	20.3	19.6	4.8	86.2	458		10	160
	19.9	20.9	20.7	20.4	0.0		458		25	404
Surface	20.4	20.6	20.2	20.6	0.0	67.6	481	12.8	5	82
	20.7	20.0	20.3	20.8	0.0			5.4	13	207
Outside	-14.0				1.0			Saving (2)	50	49
21: 0										
Control	20.4	20.4	20.2	19.8	4.8	82.8	458		7	167
	19.6	22.3	20.9	21.2	0.0		458		18	422
Surface	19.6	19.1	18.9	19.4	0.0	69.8	465	13.4	4	86
	19.0	18.8	18.8	19.6	0.0			5.2	10	217
Outside	-13.7				1.0			Saving (2)	43	49
22: 0										
Control	21.7	21.1	20.1	19.8	5.3	86.0	465		6	175
	20.0	22.3	20.7	21.1	0.0		465		20	442
Surface	19.6	19.9	19.8	20.2	0.2	66.1	443	12.8	4	90
	19.0	20.6	20.1	20.6	0.0			5.4	10	227
Outside	-14.3				1.7			Saving (2)	53	49
23: 0										
Control	21.8	20.8	20.9	19.8	3.9	86.7	473		7	182
	20.1	22.7	21.1	21.8	0.0		473		18	460
Surface	20.8	20.9	20.8	21.0	1.8	67.8	436	13.2	8	98
	20.2	20.7	21.1	21.2	0.0			6.0	20	247
Outside	-14.7				0.7			Saving (2)	-14	46
0: 0										
Control	22.4	21.4	21.4	20.7	4.3	87.8	485		9	191
	20.4	22.8	21.1	21.7	0.0		485		21	482
Surface	19.9	20.2	19.1	19.8	0.7	72.6	421	13.e	3	101
	20.2	18.9	19.1	19.7	0.0			6.4	8	255
Outside	-13.3				1.4			Saving (2)	57	47